INUNDATION AND HAZARD MAPPING DUE TO BREACHING AND OVER-TOPPING OF FLOOD CONTROL EMBANKMENT IN HARIRAMPUR

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The thesis titled " Inundation and Hazard Mapping due to Breaching and Overtopping of Flood Control Embankments in Harirampur" submitted by Sakib Mahmud, Roll No: 1014162002P, Session 2014; has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Water Resources Engineering on 23rd January 2021

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DECLARATION

It is hereby declared that, except where references are made, the work embodied in this thesis is the result of investigation carried out by the author under the supervision of Dr. Md. Sabbir Mustafa Khan, Professor, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka.

Neither this thesis nor any part of it is concurrently submitted to any other institution in candidature for any degree.

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TO MY BELOVED PARENTS

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ABSTRACT

This research on "*Inundation and Hazard Mapping due to Breaching and Overtopping of Flood Control Embankments in Harirampur*" followed a structured process for developing flood inundation and hazard maps of 13 unions of Harirampur of Manikganj. These inundation and hazard map are important outcomes of the study prepared from 1D/2D coupled hydrodynamic model results. Maps were developed using administrative union boundary and existing land use pattern on Digital Elevation Model (DEM). The model determined flood inundation information (depths and extents) and maps were produced using flood inundation information by Hydrologic Engineering Center River Analysis System (HEC-RAS) along with HEC-GeoRAS tools for processing GIS data.

The model calibration and verification were performed for 2010 and 2012 hydrological time series data at Baruria Transit (u/s) and at Bhagyakul station (d/s) of the Padma River for determining the best value of manning's roughness (n) for main river and flood plain as well. Four criteria i.e. hydrographs visualization, volume fitness, Co-efficient of Determination (R^2) and Nash-Sutcliffe Efficiency (NSE) used for selection of best roughness value (n) to evaluate the performance of the model. The roughness co-efficient (n) 0.015 for main river showed a good correlation between observed and simulated hydrograph where the best n-value was set up 0.030 for the floodplain. The modelling was an iterative process where best parameter values were determined conducting many trial and error describing the physical process. These best parameter (roughness) values were used for application of 1D/2D model for different scenarios.

Calibrated and verified model was applied for peak flood flow of 2007 and 100 year flood flow as well. Peak flood flow of 2007 at Baruria Transit (U/S) was 1,43,865 m^3/s. The 100 year flood discharge at Baruria Transit (U/S) determined using the Log Pearson Type III distributions was 152,000 m^3/s. The change of flood inundation (extents and depths) in different land classes were determined for above mentioned floods including river area and excluding river area respectively. The flood inundations information was ground trothed in the field using ITK and feed backs of stakeholders.

Four scenarios were developed as with no flood control embankment, with full flood control embankment in the left bank of river; embankment overtopping and flood control embankment breaching. Comparisons were made for flood inundation produced by model considering both river and without river areas for floods 2007 and 100 year flood respectively. Inundation of 100 years flood was more than 2007 year flood considering river areas. It was found that flood depth and land class were changed from one class to another class from the flood 2007 to 100 year floods.

Models result concluded that scenario two (with flood control embankment) was the best to protect left side unions of Harirampur. It produced maximum flood free (FF) land and least hazards. The worst flood inundation and hazard scenario one (with no flood control embankment), resulted maximum inundation and generated worst flood hazards. The scenario three (embankment overtopping) showed relatively better situation than that of scenarios four (embankment breaching) as scenario three showed the embankment protected more area until flood water overtopped embankment design crest level.

The scenarios four would provide protection until breaches occurred but breached embankment inundated area quickly.

Flood inundation determined considering inclusion of river area and found that 100 year flood inundates more area maximum of 15% for scenarios two, minimum 6% for scenarios one and almost 10% for scenarios three and scenarios four respectively than that of 2007 flood with the change of inundation in other land type class. Hazards were classified in four ranks: Very High Hazard Rank (HR4), High Hazard Rank (HR3), Medium Hazard Rank (HR2) and Less Hazard Rank (HR1). Hazard ranks were almost similar for flood water overtopping and breaching embankment.

In case of comparison between 2007 year flood and 100 year flood for overtopping, hazard rank of the Balla, Gala, Chala and Balara unions would change from HR1 to HR2 while Ramkrishnapur changed from HR3 to HR4. But the union Harukandi would remain same in HR2.Whether for breaching, hazard rank of the Balla, Gala, Chala, Balara and Harukandi unions would change from HR1 to HR2 while Ramkrisnapur would be changed from HR3 to HR4. But the union Gala would remain same in HR2. In every case, the Kanchanpur union was in HR4 as the most of its boundary goes into the river. This results was checked along with consultation to people in the field.

Above all, model results were satisfactory though data were unavailable. Using this study experiences, this model has potential and recommended to replicate for other river flood and hazard prone areas. Flood inundation and hazard maps would be useful products in different water dependent sectors for routine planning, project development and sustainable management of hydraulic structures along with the protection of the corresponding areas.

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LIST OF ABBREVIATIONS

ArcGIS	Arc Geographic Information System
ASTER	Advanced Space borne Thermal Emission and Reflection Radiation
ADB	Asian Development Bank
AVHRR	Advanced very-high-resolution radiometer
BBA	Bangladesh Bridge Authority
BTM	Bangladesh Transverse Mercator
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CEGIS	Center for Environmental and Geographic Information Services
CPP	Compartmentalization Pilot Project
CRA	Community Risk Assessment
1D/2D	One Dimensional and Two Dimensional
DEM	Digital Elevation Model
DTM	Digital Terrain Model
DL	Danger Level
EIP	Early Implementation Project
EOS	Earth Observing System
ESRI	Environmental Systems Research Institute
EPWAPDA	East Pakistan Water and Power Development Authority
FAP	Flood Action Plan
FRERMIP	Flood and Riverbank Erosion Risk Management Investment Program
FFWC	Flood Forecasting and Warning Centre
FC	Flood Control
FCD	Flood Control and Drainage
FCDI	Flood Control, Drainage and Irrigation
FF	Flood Free

FGD	Focus Group Discussion
FREMIP	Flood and River Erosion Mitigation Project
FS	Feasibility Study
GIS	Geographic Information System
GBM	Ganges- Brahmaputra- Meghna
GUI	Graphical User Interface
HDF5	Hierarchical Data Format version 5
HEC	Hydrologic Engineering Center
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Centre-River Analysis System
HEC-GeoRAS	Hydrologic Engineering Centre-Geospatial River Analysis System
HWL	High Water Level
IBRD	International Bank for Rural Development
IECO	International Engineering Company, USA
ILWIS	Integrated Land and Water Information System
IPCC	Inter-governmental Panel on Climate Change
ITK	Indigenous Technical Knowledge
IWM	Institute of Water Modelling
KII	Key Informant Interview
LANDSAT	Land Remote-Sensing Satellite (System)
LWL	Low Water Level
MODIS	Moderate Resolution Imaging Spectro-radiometer
MOWR	Ministry of Water Resources, Government of Bangladesh
MPO	Master Plan Organization
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NAM	Rainfall-Runoff Model of DHI
NHC	North West Hydraulic Consultants

NSE	Nash-Sutcliffe Efficiency
NOAA	National Aeronautics and Space Administration
PLB	Padma River Left Bank
PWD	Public Works Datum
Q/WL	Discharge/Water Level
RAS	River Analysis System
RL	Reduce Level
RS	Remote Sensing
SAR	Specific Absorption Rate
SoB	Survey of Bangladesh
SRTM	Shuttle Radar Topographic Mission
TIN	Triangular Irregular Networks
USA	United States of America
USGS	United States Geological Survey
USACE	United States Army Corps of Engineers
WARPO	Water Resources Planning Organization
WL	Water Level
WRF	Weather Research and Forecasting Model
WRS	Water Resources System

Chapter 1: Introduction

1.1 Background and Problems Statement

Bangladesh is a low lying and flat deltaic country located at the confluence of three world largest rivers the Ganges, the Brahmaputra, the Meghna and these rivers constitutes the GBM basin. About 92.5 percent of GBM basin area of aforementioned rivers lies outside of the country (Rouf.T.2015). The country is homogeneous with only a few hills in the North West, Southeast and Northeast parts of the country. Ground slopes of the country extend from the north to the south and the elevation ranging from 60 meters in the north to one meter above Mean Sea Level (MSL) at the boundary at Tantulia (most south) and at the coastal areas in the south (Islam 2012).

Due to its geographic location, Bangladesh is one of the most natural hazard and disaster risk prone country in the world where storm surges, cyclones, floods, river bank erosions, water logging and droughts are frequently occurred affects the lives and livelihoods of the people of specific regions (Nasreen 2004). Among all of the natural disasters, flood and river erosion are severe most problems in Bangladesh causes hazards in every years.

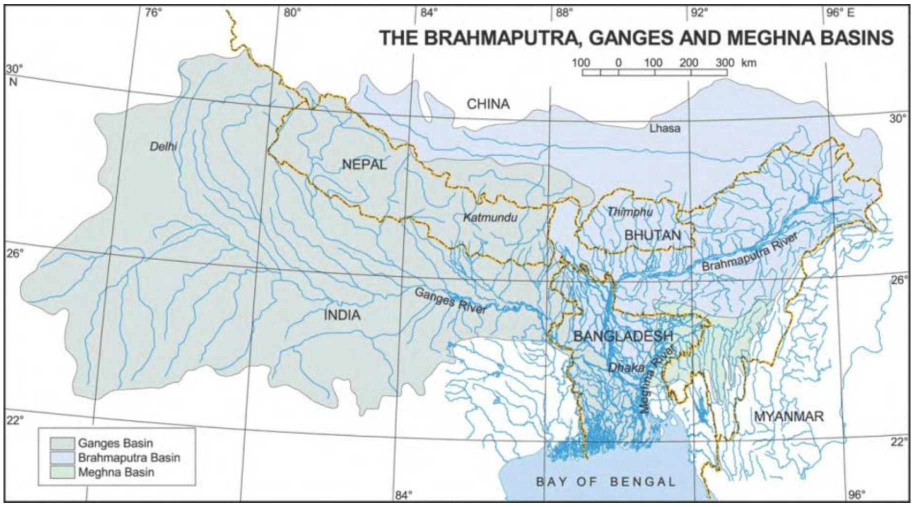
Flood is the most dominant and recurrent hazard event, at least 20% areas are being flooded every year and sometime maximum of 68% areas inundated in case of severe flood (Disaster Management Bureau 2010). Historically, Bangladesh has experienced several big floods of high magnitude in 1974, 1984, 1987, 1988, 1998, 2000 and 2004 (FFWC 2005). Floods of 1988, 1998, 2004 and 2007 inundated about 61%, 68 %, 38% and 45% of the total area of the country, respectively (Rahman et al. 2007).

River Erosion is an acute problem of all upazillas located besides the major river system (i.e. the Ganges, the Bramhaputra, the Padma and the Upper and Lower Meghna River) and also Minor River of all hydrological regions. On an average every year almost 6,000 ha of land area (net area) are being eroded causes damage to rural homestead and infrastructures, loss of agricultural land, urban infrastructures, forest ecosystem and makes the dwellers in vicious circle of poverty and forces people to migrate to live in urban slum areas.

1.2 River Systems and their hydro-morphological characteristics

The three major rivers (the Ganges, the Brahmaputra and the Meghna) acts as the main arterial system and their hydro-morphological characteristics and their responses are responsible for flood. This system allows almost 100% flood water of GBM basin (Figure 1-1) to pass through Bangladesh and ultimately falls into the Bay of Bengal.

The Brahmaputra-Jamuna River System draining the northern and eastern slopes of the Himalayas is 2900 km long and has a drainage area of 573,500 km^2. In Bangladesh, the reach length of this river is only 240 km. It has several right bank tributaries: the Teesta river, the Dharla river, the Dudhkumar river, the Bangali and the Hurasagar and there are two left bank distributaries-the Old Brahmaputra and the Dhaleswary Rivers. It is a braided river with an average bank full discharge width roughly about 11 km. The channel has been widening from an average of 6.2 km width in 1834 to 10.6 km width in 1992 (FAP16, 1995). Having an average annual discharge of 19,600 m^3/s, the river drains an estimated $620x10^9$ m^3 volume of water annually goes to the Bay of Bengal. The discharge varies from a minimum of 3000 m3/s in dry season to a maximum of 1, 00,000 m^3/sec in wet season, with bank-full discharge of approximately $48,000m^3/sec$. It has an average surface slope of 7 cm/km (Hossain.



1992, BWDB, 2010)

Figure 1-1: GBM Basin of the Ganges, the Brahmaputra and the Meghna River System (Source: www.lahistoriaconmapas.com, accessed on 13th January, 2018)

T**he Ganges River System** is one of the major river systems of GBM as well as of the country. The Bengal delta occupies a unique position among the largest deltas of the world for its varied, complex river and drainage system and having hydro-morphological dynamics. The Ganges has a total length of about 2,600 km and a catchment area of approximately 907,000 km^2. Within Bangladesh, the Ganges (258 km long) starting from the western border with India to its confluence with the Jamuna at Goalanda ghat, located some 72 km west of Dhaka (BWDB, 2010).

The **Padma River System**, about 120 km long, running from the Goalanda ghat confluence to Chandpur where it joins the Upper and Lower Meghna confluence. The total drainage area of the Ganges or the Padma river is about 1,087,400 km^2, of which about 46,300 km^2 lies within Bangladesh (Banglapedia, 2014). The combined flows of the Jamuna and the Ganges rivers constitute the flow of the Padma River. Before the avulsion of Jamuna River, the flow was a continuation of the Ganges River only, and the Rennel's map shows that the river passed further south than the present course (Habib at el.2004). After the confluence of the Ganges and the Jamuna River, the river flows in the name of the Padma River through Rajbari, Faridpur (on the right bank) and Manikganj, and Munshiganj (on the left bank)

Several areas of these districts situated along the Padma river bank become flooded in every year due to overtopping and breaching of flood control embankments. Among these areas, Faridpur Sadar and Char Bhadrason in Faridpur district and Harirampur in Manikganj district are the notable and local communities of these areas become victim of flood and erosion occurrence (BWDB, 2014; Habib at el 2004; Rahman 2014). The annual mean discharge of the Padma is 28,000 m^3 /s, and bank full discharges in the range of 43,000 m^3/s to 75,000 m^3/s. The average size of the bed material is about 0.10 mm. Geo-morphologically, the river is still young.

A reach of about 90 km is almost straight and the plan form of the river is a combination of the meandering and braiding type. The variation of the total width of the river is quite high, ranging from 3.5 km to 15 km. The slope and the bed material sizes of the rivers vary within a range of 8.5 to 5 cm per km, and 0.20 to 0.10 mm, respectively. With respect to plan form, the Jamuna is distinctly a braided river, while the Ganges and Padma rivers fall in between braided and meandering rivers, i.e. wandering rivers. The bank erosion rates of the rivers are remain almost the same (Habib at el. 2004).

The Meghna River System: The Upper Meghna River originates from the Shillong Plateau and Northern hill foothills. It is a canaliform type of meandering river and locally anabranches. It is relatively a small width but deeper river having a bank full discharge width of 1 km. The river has a catchment area of 77,000 km^2 and a length of about 900 km. The river drains 151×10^9 m^3 volume of water annually to the Bay of Bengal. The average mean annual discharge is 4800 m^3/s and dominant discharge is 9,500 m^3/s. The lower reach of the river the Lower Meghna River is tidal during December –April with negligible residual flow and reaches a maximum discharge of 20,000 m^3/s during monsoon. The net discharge through this Lower Meghna River varies from 10,000 m^3/s in the dry season to 160,000 m^3/s in the wet season (BWDB, 2010).

1.3 Overall Study Objectives and Expected Outcomes

The overall study objective is to calibrate and validate HEC-RAS 1D/2D coupled hydrodynamic model as a water resources assessment tools for the selected river reach of the River Padma using observed discharge and water level and to generate spatial distribution of flood inundation (extent with depth) and Hazard mapping under breaching and overtopping of the flood control embankment even with river training works in the left bank of the Padma River.

The **specific objectives** of the researches are as follows:

a) Calibrate and validate HEC-RAS 1D/2D coupled model for selected reach of the River Padma against observed water level and discharge.
b) Apply the model to generate flood inundation map (extent and depth) in Harirampur due to breaching and overtopping of flood embankment.
c) To generate a hazard map using model results for each union of Harirampur for the above two scenarios from model outputs.

Expected outcomes of the researches are as follows:

a) A calibrated and validated hydrodynamic model of selected river reach of the Padma River.
b) The developed HEC-RAS 1D/2D coupled model will be useful in the planning, designing, operating and maintaining of flood control structures and other measures.
c) The hazard maps prepared based on flood inundation map for two different scenarios (Breaching of Flood Control Embankment and overtopping of Flood Control Embankment) and will be useful to identify the areas of very high hazard, high hazard, medium hazard and low hazard in the context of flood Hazards of the study area.

1.4 Rationale of the Study

Every year the Padma River flood inundates nearby or adjacent flood plain areas at different depths. The flood extent and depth of flooding depends on the flood frequency and its magnitude of the flood level which comes annually. The flood inundation maps prepared from model outputs will be useful for infrastructural planning and development, improvise existing agricultural and fisheries practices and aware local people to protect their crop and wealth resources. Flood Control measures like the flood embankments including river training works of water development projects could be properly planned to protect the lands from impact and damage of flood.

Flood control embankments breaches due to many reasons i.e. foundation failure, poor workmanship, less compaction, river erosion while embankment overtopping is due to not doing regular adequate maintenances of the embankment. This unexpected breaching and overtopping of flood, inundates vast areas within shortest possible time without warning and causes severe damages to the standing crops, social infrastructures and wealth etc. creates untold misers to the life and livelihood of the inhabitants.

The flood inundation and extent map for specific flood event could be prepared from model results with necessary ground trothing. Modelling is a scientific and conceptually physically based approach where flood inundation assessment requires a two dimensional model. However, study of flood inundation could be done using coupled one dimensional (1D) and two dimensional (2D) hydrodynamic model which includes flood plains as a part of its model domain. For example, HEC-RAS was being used widely to develop flood inundation map in many studies (Hazarika 2007, Knebl et al. 2005, Hicks at el. 2005, Abera 2011, Khan 2009).

Noteworthy to mention that not many studies were being carried out to determine flood extent, its inundation depth and hazard mapping for such inundation using mathematical model results of the mighty Padma river. A few studies have been carried out using satellite images and GIS (Bhuiyan 2014, Islam et al. 2010, Hasan 2006) for flood inundation mapping but accuracy of flood inundation map depends on the water surface elevation generation.

The automated floodplain mapping and analysis using HEC-RAS and HEC-GeoRAS tools would provide more easy, efficient, effective and standard results and saves time and resources. The study outcome would help the water resources planner to prepare river flood hazard maps to identify the areas with hazard at different scale caused by river flood due to embankment breaching and overtopping.

1.5 Study Area/ Model Domain

The study area has been selected 48 km reach of the River Padma including total Harirampur of Manikganj district. Harirampur has 13 unions of which 10 unions falls on the left bank and remaining 3 unions falls in the charlands of Padma River. It occupies an area of 243.06 km^2 located between $23^0$38' and $23^0$48' north latitudes and $89^0$50' and $90^0$03’ east longitudes *(*Population and Housing Census.2011). The upstream of the model domain is the Baruria Transit Station of BWDB in Harirampur, immediate after the confluence of Ganges and Jamuna River where BWDB has both surface water level (SW91.9L) and discharge stations. Bhagyakul at Munshiganj considered as the downstream boundary where BWDB has only water level station (SW 93.4 L). The model domain has been selected in such a way that calibration and validation could be performed in comparison with water level station of the Baruria Transit. The model domain is shown figure 1-2 as below.

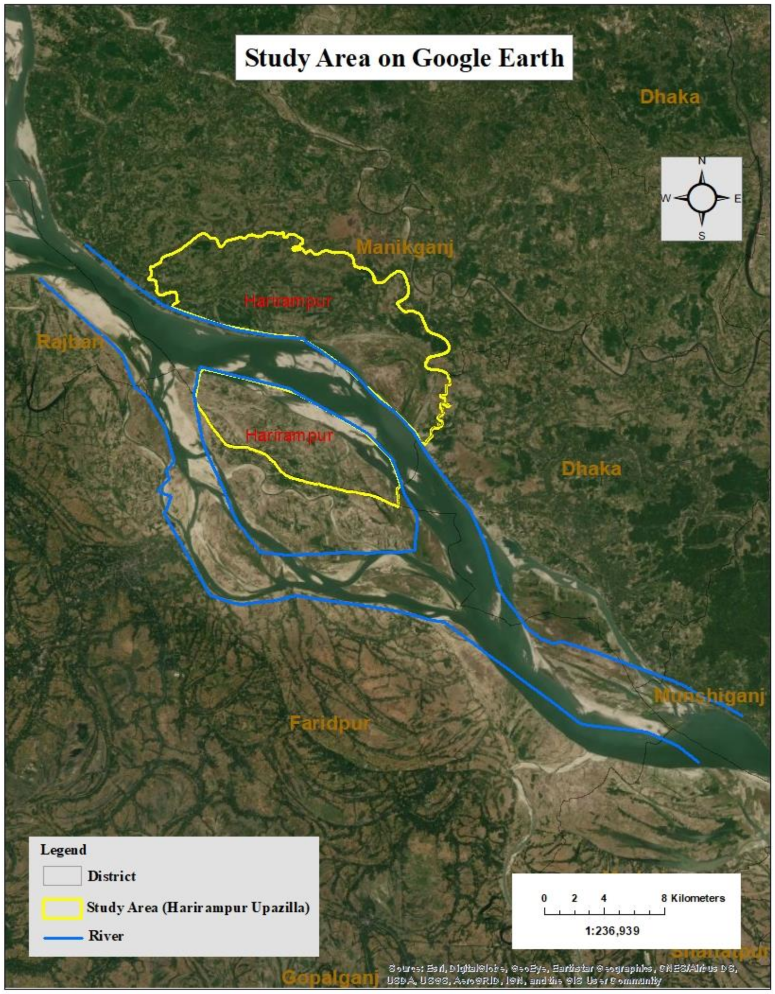


Figure 1-2: Study Area Shown in Yellow Line in the Satellite Image Map

1.6 Structure of the Study Report

The thesis contains eight chapters with annexes and organization of the chapters were as follows:

Chapter One provides the background of the study and present problem statement. It also draws attention to the study objectives, expected outcomes, study area/ model domain, rational of the study and organization of the chapters of the study report.

Chapter Two describes the flood phenomenon in details, its causes, its consequences, flood and Water Management Practices in Bangladesh over the years as a flat deltaic lower riparian country;

Chapter Three provides mainly the literature review and provided brief description of the selected previous studies (both national and international) on flood modeling and flood inundation under different scenarios considered embankment overtopping, breaching and other structural failure.

Chapter Four describes baseline setting of the study area including social, environmental, hydro-morphological issues, flow regime and flood information etc. and many others. It is needed to understand the arenas which are being affected due to flood inundation and created hazards;

Chapter Five presents salient features on the HEC-RAS, hydrodynamic model, HEC-GeoRAS and ArcGIS and discusses about data collection, the methodology of frequency analysis. This chapter also discusses the methodology of DTM creation and pre-processing of HEC-GeoRAS.

Chapter Six describes in detail the approach and methodology, data collection and model setup of the study in a system diagram, process of model setup and detail step wise discussion.

Chapter Seven presents the model calibration and validation results, the results of model application under two different scenarios (inundation due to embankment breaching and inundation due to over toppings) while two more scenarios (Inundation without any flood control measures and with flood control measure) were also considered and applied for better understanding the impact of breaching and overtopping scenarios and to develop the flood inundation maps and hazards maps of the Harirampur. This chapter also explains the probable use of Flood Hazard Map against flooding such as the flood of 100 years return period and peak flood of 2007.

Finally, **Chapter Eight** describes conclusions, recommendations and limitation of the study.

Chapter 2: Flood and Water Resources Management Practices

2.1 Introduction

Flood is the most common natural disasters that affect societies as well as the development around the world. Dilley et al. 2005 estimated that more than one-third of the world's land area is flood prone affecting 82 percent of the world's population. This chapter discussed about floods, flood types and its dynamics, natural hazards, flood hazard map, initiatives already made over the years for flood management and its consequences from social, environmental and hydro-morphological point of view. It also provide an overview of the present flooding situation as well as flood and Water Resources Management measures (both structural and non-structural) that are being practiced over the years in Bangladesh.

2.2 Natural Hazard

Hazard is considered as a harmful incident and it causes damage to humans, property, ecosystem and the environment. Natural hazard is probability of occurrence of a potentially damaging phenomenon within a specified period of time, where risk is the actual exposure of human value to a hazard and is often regarded as the combination of probability and loss within a given area (Bhuiyan, 2014). Hazard is defined as a potential threat to human's lives and livelihoods, their welfare and risk as the probability of a specific hazard consequence. When large numbers of people exposed to hazard are killed, injured or damaged in some way, the event is termed as a **disaster**.

Hazards associated with flooding is divided into a) primary hazards that occur due to contact with water, b) secondary effects that occur because of the flooding, such as disruption of services, health impacts i.e. famine and disease, and tertiary effects i.e. changes in the position of river channels. Natural hazards, i.e. urban flood, river flooding, waterlogging, cyclone and storm surge, volcanos, landslides, drought, earthquakes and tsunamis. Pictorial view of different kind of hazards and their consequences in Figure 2-1.

2.3 What is Flood?

If an area goes under water and remains for short time it is termed as ***inundation.*** But when inundation remains longer time and it causes damage to the natural ecosystems, wealth and property and life and livelihoods, disrupts communication and brings harmful effects to not only human beings but also to the flora and fauna of ecosystem, then it is termed as ***flood***. Flood perception varies from person to person, area to area, hydrologic regime to regime, environment to environment and countries to countries etc. One of the most compressive accounts of flood perception in a developing country's environment given by ***Cunny***(1983) , who described the perception of the farmers in the West Bengal of India, who

Figure 2-1: Different types of Natural Hazards and their consequences (source: google)

"indicated that a flood has occurred when water remains in the field long enough to waterlog, when water stands or drowns livestock, when water currents scour the land, when floods deposit sand that cannot be economically removed, when floodwaters increase the salinity in the fields, when water rise above the housing plains, when successive floods prevent immediate recovery, or when fish ponds are inundated and fry and fingerlings are swept away. For land less agricultural laborers, a destructive flood is one that reduces their job prospects or prevents them from going elsewhere in search of work. For non-farm villagers, a flood is defined as water penetrating and damaging commercial buildings, water penetrating and damaging houses, or water preventing the transport of goods. Most rural people said that a flood was when water rise faster than one could take preventive maintenance"

2.4 Historical Evaluation of Flood Investigations

Historically, Bangladesh experienced and affected by many severe floods over the years in 1954, 1955, 1961, 1962, 1964, 1970, 1971, 1974, 1984, 1987, 1988, 1993, 1998, 2004 and the last Cyclone-Sidr in 2007. Several investigations, researches and studies by international and local scientific institutes made over the years since Krug Mission Report in 1955 till to date to find out cause, effect and mitigation measures (both structural and non-structural) of floods.

2.5 Flood Classification and its types

Flooding is the most common natural disasters, creates environmental and social hazard in world. This is due to the vast geographical distribution of river floodplains, flat and low-lying coastal areas. Flood can be described as an overflow of water over normally dry land. The inundation of a normally dry area caused by rising water in an existing conveyance of waterway such as river, stream, or drainage ditch, ponding of water at or near the point where the rain fall occurs. Therefore, flood may be classified in many ways described as below:

2.5.1 Flood Classifications Based on Goods and Services

Flood classification may be made based on the user demand for goods and services: The connotation of the existence of a user demand for goods and services produced by floods, either positive or negative, it is important for the concepts of normal, optimal, high and low floods.

a) ***Normal Flood***: That would be an expected flood for which a specific user is prepared and for which they implicitly or explicitly account in their respective planning.
b) ***Optimal Flood:*** gives maximum benefits for a specific user (CPP, 1996) and ecosystem.
c) ***High Flood***: causes unexpected flooding in both rural areas and urban areas, damages to agricultural crops, communication infrastructure, plant and vegetation, human resources, homestead and negative impact on socio-economic environment, communication system and fisheries resources.
d) ***Low Flood***: damages to fish habitat, reduce recharge to ground water aquifers and increasing draught proneness. This occurs in dry year and water availability from outside territory is low and rainfall is low too.

2.5.2 Flood Classification Based on Different Sources

Bangladesh is a largely low-lying, flat and deltaic flood plain and prone to following types of flooding. The physical characteristics of land, geographic location, multiplicity of rivers, and monsoonal climate attribute to the floods taking place annually and causing serious social, economic and environmental damages. Annual flood contributes to the traditional agriculture practices depending on the replenishment of soil, its fertility and water required for the cultivations. Types of floods are also classified as bellows:

i) **Monsoon flood** occurs because of heavy and incessant rainfalls in the upper catchments as well as inside the country in wet season (over 80% of the annual rainfall occurs in wet season). The severe monsoon floods occurred in 1987, 1988 and 1998. As per BWDB annual flood reports 2016, the flood affected areas were estimated at 100,250 km^2 by the 1998 flood (accounting 68% of the country), 89,970 km^2 by the 1988 flood (61%), and 57,300 km^2 by the 1987 flood (39%).

ii) **Flash flood** occurs in the North-Eastern Zone (NEZ), South-Eastern Zone (SEZ), and extreme Northern Zone (NZ) areas during April to May where hilly or mountainous terrain exists. This flood is characterized by a sharp rise of peaks followed by a relatively rapid recession often causing high flow velocity for steep slope. The cause of flash flood is due to extremely high rainfall intensity occurring locally during monsoon and transitional seasons. The concentration of flood runoff is quite rapid within several hours at the shortest which results inundation and destructive damages to agricultural standing crops, fisheries, homestead, plants and vegetation and other properties.

iii) **Local Rainfall flood** is due to excessive rainfall of long duration in the monsoon, generating water volume in excess of the inbuilt drainage capacity of urban drainage system causes local rainfall floods.

iv) **Major River flood** from major rivers (the Ganges, the Brahmaputra, the Padma and the Meghna) generally rises slowly. The period of rise and fall extends over 1-20 days or more. Spilling through distributaries and over the river banks causes most extensive damage, particularly when the three rivers water level rise simultaneously.

v) **Tidal flood** occurs in the coastal rivers and estuaries in the South West, South Central and South Eastern Zone. The three hydrological regions of Bangladesh face flooding situation twice a day due to astronomical tide of the Bay of Bengal. At the time of spring tide, which occurs fortnightly, causing tidal water floods in large area.

vi) **Storm-Surge and Cyclonic flood** occurs in the coastal areas due to tropical cyclones and storm surge in the Bay of Bengal causes severe disaster and extensive damage to the lives, livelihood and properties. Cyclones are predominant during post-monsoon (October-November) and pre-monsoon (April to June). Approximately 12000 Km^2 in 19 Coastal Areas districts is prone to storm surge and cyclonic flood. This flood causes the most serious and widespread disasters. Cyclones form the Bay of Bengal often hit the Southern, SC and SE coastal areas and bring heavy rainstorms causing flood and storm surges due to accompanying strong winds. The coastal areas are prone to flooding by heavy rainstorms coupled with water level rises. The dangerous situations during cyclones are not only floods but also strong winds and storm surges that attack destructively the coastal areas.

vii) **Man Made Flood:** Infrastructures (mainly embankment, roads, urban drainage system) development without keeping adequate provision for unimpeded drainage causes flood during heavy rainfall. The man-made factor was one of the main reasons for rapid increase in flood depth and excessive duration of flood during devastating rainfall occurred in September-October any region of Bangladesh. Reduction of flood storage areas due to filling low lands and depression is also exacerbating the flooding condition. The map shows different types of floods occurs in different region of Bangladesh prepared by WARPO is shown in Figure 2-2.

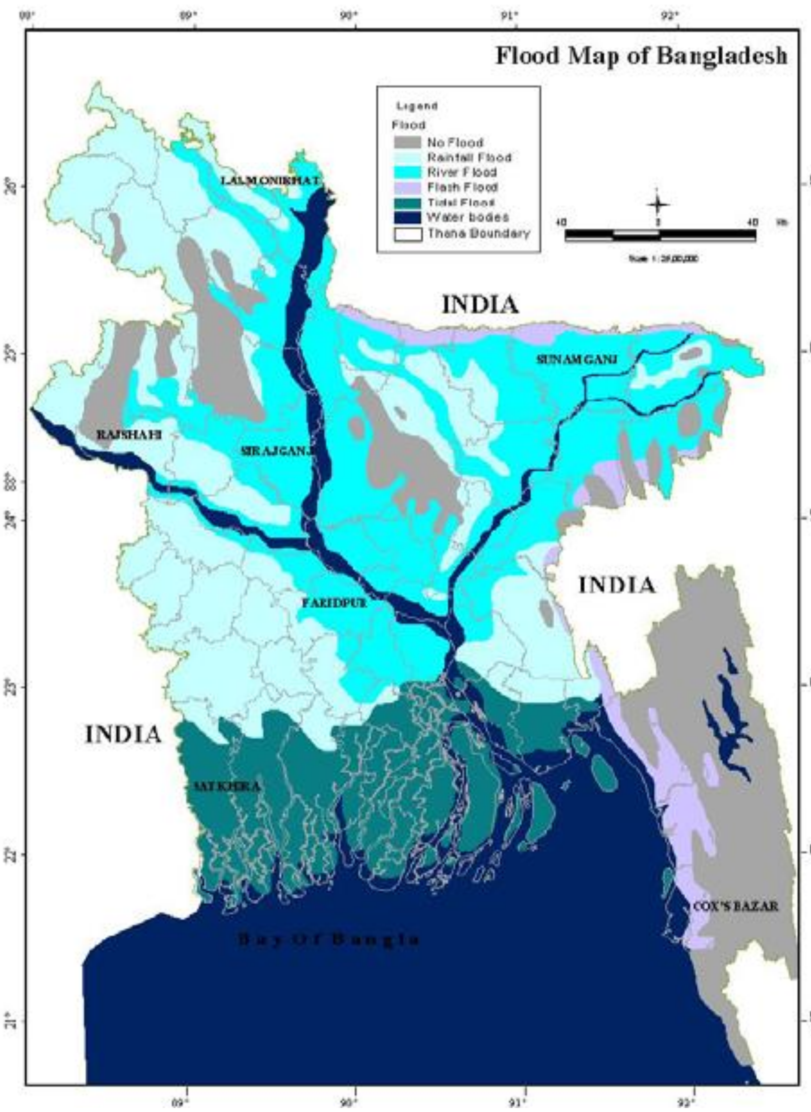


Figure 2-2: Types of Flood in different parts of the country (WARPO, 2002)

2.6 Causes of Flood

Bangladesh through its integrate network of river system, drains a catchment of about 1.76 million km^2 of GBM basin of which only 07 percent lies within Bangladesh. Being a lower riparian country, more than 90 percent of the stream flow with high sediments load comes from upstream catchment passes through Bangladesh.

Floods in Bangladesh occur due to natural, anthropogenic and development activities of the country. The main reasons are excessive precipitation, low and flat topography with mild slope of the country; but others also included are:

a) Tectonic uplift of the Himalayas resulted increased erosion and rate of sediment. The rivers of this country are more potential for erosion. This huge sediment due to erosion from upstream dumped in Bangladesh choking the river channels and conveyance making them inefficient and incapable of conveying the flood water and reducing hydraulic radius results flooding occurs.

b) Excessive rainfall generates huge runoff in a short time span in upstream catchment and within the country.
c) Runoff generated by heavy local rainfall cannot be drained out quickly due to high stage of Outfall Rivers.
d) Deterioration of channel drainage capacity by natural siltation, shoal formation and man-made obstruction.
e) Drainage congestion due to uncoordinated and unplanned development activities by different development, lack of adequate number of interventions, encroachment of river and flood plains.
f) Flat topography, which slows drainage rate, tidal surge, sea waves and global climate change.
g) Deforestation in upper catchment such as the Himalaya and hilly areas reducing interception rates means shorter lag time and higher peak discharges.
h) Cyclones from the Bay of Bengal causes and contribute to increase coastal flooding and prolong the duration of flood in Bangladesh.
i) Rapid development of urban and communication system without keeping proper flood flow opening hinders monsoon water to pass easily and also inadequate drainage system cannot drain runoff easily causes flood.

Besides these above reasons, a number of issues came up after the flood in the year 1998 responsible for floods are: a) The role of *EL-Nino* and *La-Nina; b)* The Global Climate Warming; c) The role of *Tusnamis* in the Bangladesh coast reportedly to have been originated from the earth quakes in the Bay of Bengal and d) Melting of Glacial ice in the Himalayas etc. The cause effect relationship of the floods in Bangladesh presented in the following matrix developed shown in Table 2-1:

Table 2-1: Cause and Effect Relationship of Floods

Flood Types	Affected regions	Occurrence period	Cause of floods	Effects of Floods
Flash Floods	Eastern and northern hilly streams	Pre-Monsoon (April-May)	-Excessive Rainfall in short span of time -Deforestation in upper catchment -Uncoordinated development in upper catchments. -Melting of glacial ice	-Sharp rise of water level -Sudden damage to Agriculture -Wealth, livestock and Property. -High velocity of river flow -Erosion and degradation
Local or Rainfall Floods	Upper part of NW & SW regions, Middle strip of NE & SE region	Monsoon (May to September)	-High rainfall for long duration -Flat topography and slow drainage -Rise of outfall Water Level -Siltation reduces conveyance capacity	-Flood exists for long duration causes environmental hazard -Water quality deterioration -Disruption of communication and Agricultural damage
Major River Floods	Flood plains of major rivers and their distributaries	Monsoon (May to September)	-Over bank spilling -Flat topography -Slow drainage -Tidal surge & waves -Flood peaks coincidence	-Vast area are being affected and crop damage -loss of human property -loss of livestock & fishery -Huge flood plain siltation -Severe erosion
Tidal Floods	19 Coastal districts of	Round the year	Rise of outfall rivers level due to astronomical tides	-Impended drainage -Aggravate Upstream flooding

Flood Types	Affected regions	Occurrence period	Cause of floods	Effects of Floods
	SW, SC and SE regions			-Increase siltation and soil salinity in tidal areas
Storm surge and Cyclonic Floods	Specific Coastal Area	Occasionally (April to June)	Tropical cyclone in Bay of Bengal	-Major thrust to existing physical environment -collapse socio-economic environment -Huge loss of property and livestock, agricultural damage -Communication disruption

2.7 Flood and its Impacts

Normal floods are blessing for a country which provides vital moisture content, soil fertility and nutrient to the land through alluvial silt deposition in floodplains. Floods increase the habitat areas for aquatic flora and fauna. It also increases the dilution of water quality creates better aquatic environment clears all sludge and increase water quality. Floods also provide supports to world largest mangrove ecosystem, the Sundarban (the World Heritage) located in the most south-western part of south western (SW) region of Bangladesh. Ensuring rich flood flow from the upstream increase the brackish flow volume for longer period immensely benefits the Sundarban.

Moderate to extreme floods are of great concern, as it inundate large areas and cause widespread, infrastructures damages, including physical damages to agricultural crops, buildings and other infrastructures, social and homestead forest, Livestock and Poultry, Fisheries, social disruptions in vulnerable groups, livelihoods and local institutions, and direct and indirect economic losses. The majority of flood disaster's victims are poor people, who suffer most and are the first casualty of such incidents (WWAP 2006). The flood hazard in recent times is getting more and more frequent and acute due to growing population, socioeconomic activities and massive developments in the floodplain at an ever increasing scale. The flood damage were US $ 1.4, 2.0, 2.3, and 1.1 billion in floods of 1988, 1998, 2004 and 2007 occurred in Bangladesh respectively (World Bank 2007).

Normally, 25-30% areas are being inundated during monsoon season along the river (Hossain 2003). In case of extreme floods 50-70% of the country are inundated extending the areas far beyond the riverbanks (Hossain 2003). The causes of floods in Jamuna River are heavy rainfall in monsoon, snowmelt, enormous discharge coming from upstream, levee breaching, river siltation etc. (Shahidul et al. 2003, FFWC 2008).

The IPCC research reported that Bangladesh is highly vulnerable to climate changes impacts (IPCC 2013). According to IPCC (2013), both monsoon rainfall and sea level will be raised. Because of increased monsoon rainfall and raised sea level, flood inundation will be increased. Furthermore, about 80 percent of the annual rainfall occurs in the monsoon (June to September) across the river basins (Rouf.T.2015).

Now a days due to implementation of river management activities, inadequate channel improvement and maintenance of water development projects, water logging problems are surfacing gradually in new and newer areas of inlands and also in 19 coastal areas of Bangladesh.

2.8 Historical Flooding Statistics

Bangladesh is prone to serious and chronic flooding. Even in an average year 30% of the landmass is inundated and previous severe floods have affected 68% of the country (as in 1998). 68% of the country is within 10m above mean sea level and 80% is classified as floodplain as Bangladesh is principally the delta region of South Asia's great rivers, Floods occurs on a regular basis, recent notable and catastrophic floods have occurred in 1988 (return period of 1 in every 50 to 100 years), 1998, 2004, 2007,2010 and 2017. Table 2-2 summarizes flood and it inundation statistics.

The catastrophic floods of 1987 occurred throughout July and August affected 57,300 km^2 of land, (about 40% of the total country) and was estimated as once in 30-70 year event. The seriously affected regions were on the western side of the Brahmaputra River, the area below the confluence of the Ganges and the Brahmaputra and considerable areas north of Khulna.

The **1988** flood was also of catastrophic nature, occurred throughout August and September. The flood inundated about 82,000 km^2 of land, (about 61% of the country area) and its return period was estimated within 50–100 years. Rainfall together with synchronization of very high flows of all three major rivers in only three days aggravated the flood. Dhaka, the capital city, was severely affected and inundated. The flood was lasted 15 to 20 days.

In **1998**, over 68% of the total country was flooded, including half of the capital city Dhaka. It was similar to the catastrophic flood of 1988 in terms of the flood extent. A combination of heavy rainfall within and outside the country, synchronization of peak flows of the major rivers contributed to the flood. 30 million people were homeless and the death toll reached over a thousand. The flooding caused damages of standing crops, animals and unclean water resulted in cholera and typhoid outbreaks. Few hospitals were functional because of damage from the flooding and those that were had too many patients, resulting in everyday injuries becoming fatal due to lack of treatment. Crops of 700,000 hectares were destroyed, 400 factories were forced to close and there was a 20% decrease in economic production. Communication system within the country also became difficult.

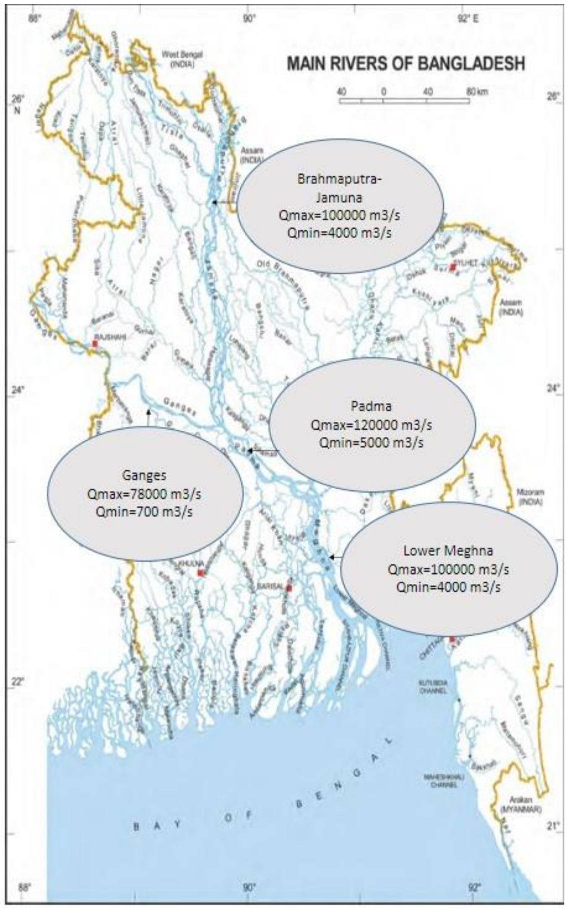


Figure 2-3: Discharges in the Ganges, Padma, Brahmaputra and Lower Meghna River (Source: Haskoning.1992, Thorne et al 1993, Halcrow 1993, FAP24 and Others www.lib.pmo.gov.bd, accessed on 13th January, 2018)

The **2004** flood lasted from July to September and inundated 38% of the country. At the time of July 2004 floods, 40% of the capital, Dhaka was under water. 600 deaths were reported and 30 million people were homeless. 100,000 peoples alone in Dhaka suffered from diarrhea from the flood waters. Bridges and culverts were destroyed, the death toll rose to 750 and the airport and major roads were mostly flooded. The damage to schools and hospitals were estimated at $7 billion. Rural areas also suffered, the rice crop production was devastated and the production of the important cash crops such as jute and sugar were very low.

In **2007**, about half of Bangladesh was seriously affected by monsoon flooding. This was caused by excessive rainfall in catchment areas of Nepal, Bhutan and Northern Indian, floods in July and September affected 13.3 million people – 6 million of them children – in 46 districts. In 2017, almost 42 percent areas in Bangladesh was affected by river flood generated from upstream (FFWC, BWDB, 2019)

The flood statics presented in the table 2-2 indicated that up to now the floods inundated more than 29% areas are 1955, 1963, 1970, 1974, 1987,1988,1998,2004,2007,2015,2016 and 2017. Earlier big flood comes after certain interval gave breathing time to people and management to coupe the damage of flood but after 1987 and onward it does not maintain any time interval rather severe flood occurred continuously for example 1987-1988 and 2015-2017 respectively.

Table 2-2: Statistics of Flood Affected Area in Bangladesh

Year	Flood Affected Area (around)		Year	Flood Affected Area (around)		Year	Flood Affected Area (around)	
	km^2	%		km^2	%		km^2	%
1954	36,800	25	1977	12,500	8	2000	35,700	24
1955	50,500	34	1978	10,800	7	2001	4,000	2.8
1956	35,400	24	1980	33,000	22	2002	15,000	10
1960	28,400	19	1982	3,140	2	2003	21,500	14
1961	28,800	20	1983	11,100	7.5	2004	55,000	38
1962	37,200	25	1984	28,200	19	2005	17,850	12
1963	43,100	29	1985	11,400	8	2006	16,175	11
1964	31,000	21	1986	6,600	4	2007	62,300	42
1965	28,400	19	1987	57,300	39	2008	33,655	23
1966	33,400	23	1988	89,970	61	2009	28,593	19
1967	25,700	17	1989	6,100	4	2010	26,530	18
1968	37,200	25	1990	3,500	2.4	2011	29,800	20
1969	41,400	28	1991	28,600	19	2012	17,700	12
1970	42,400	29	1992	2,000	1.4	2013	15,650	10.6
1971	36,300	25	1993	28,742	20	2014	36,895	25
1972	20,800	14	1994	419	0.2	2015	47,200	32
1973	29,800	20	1995	32,000	22	2016	48,675	33
1974	52,600	36	1996	35,800	24	2017	61,979	42
1975	16,600	11	1998	1,00,250	68	2018	33,941	23
1976	28,300	19	1999	32,000	22			

Source: FFWC, BWDB, 2019

2.9 Flood in the Study Area

The study area is Harirampur consists of 13 unions of which 10 unions are located in left sides of the Padma Rivers in the main land and other 3 unions lie charlands within the conveyance of the mighty Padma River. The left sides of the study areas along with charlands in middle of river falls in the Harirampur. The mighty river carries the combined flow of both the Ganges and the Brahmaputra rivers. The hydrograph of the Padma River at Baruria Transit shown in Figure 2-4 for year 2007.

Usually two types of floods, riverine flood and rainfall flood occur causes severe damages in every year in the study area. Riverine floods from the spilling of major rivers flow and their tributaries and distributaries generally rise and fall slowly over 10–20 days or more and can cause extensive damage to property and the loss of life. Depth and extent of floods and associated damage are extensive when the major rivers flood peaks reaches in same time. Rain flood is caused by high intensity local rainfall of long duration in the monsoon as a results flood water cannot cleared due to high water level in the Outfall Rivers. The extent and depth of flooding in the study area varies depending on the amount and intensity of local precipitation and current outfall water levels in the Padma Rivers that controls drainage from the land.

The highest flood discharge of Padma River at Baruria Transit is 142,500 m^3/sec in 2007 was severe flood inundated about 62,300 km^2 which is about 42% of the country. This almost inundated the total Harirampur.

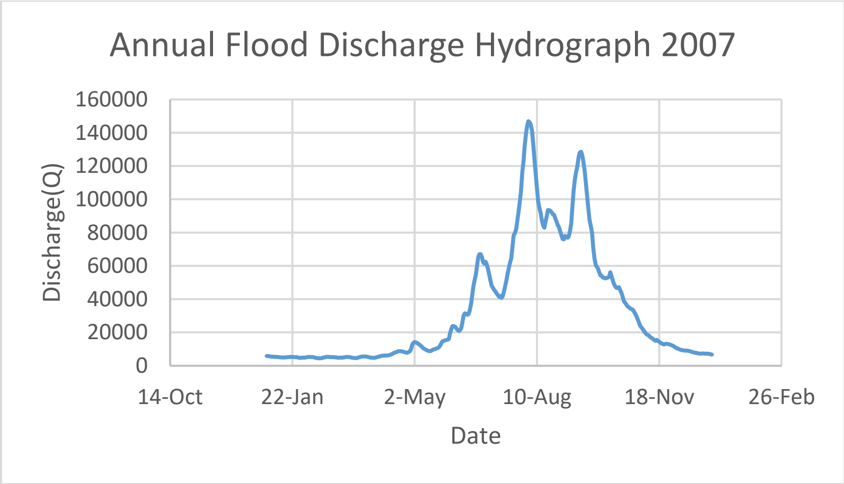


Figure 2-4: Annual Flood Discharge Hydrograph of Padma River at Baruria Transit 2007

2.10 Past Flood and Water Resources Management Initiatives/ Studies

Bangladesh Water Development Board (BWDB) the then East Pakistan Water and Power Development Authority (EPWAPDA) since its inception in 1959 has undertaken responsibility to protect areas from flood and its damage through several flood control projects in the name of FC, FCD and FCDI projects mainly the major and medium scale.

EPWAPDA prepared the first flood control master plan named as IECO Master Plan in the year 1964 consists of 58 big flood control, flood control and drainage projects and implemented in early sixties. Gradually irrigation component was added in the Flood Control and Flood control and drainage projects and termed as Flood Control, Drainage and Irrigation Projects (FCDI).

After independence in the year 1971, the initiative IBRD (International Bank of Rural Development) sector study was taken in 1972 for green revolution to boost up the agricultural production and BWDB also initiated the Dutch Aided short gustation two year project in the name of EIP (Early Implementation Project 1974). Latter on 1986 National Water Plan prepared by MPO (Master Plan Organization), presently the WARPO and which was updated in 1991 by the Water Resources Planning Organization (WARPO) and prepared a number of project portfolios for implementations to meet up short term and long term objectives. Now WARPO acts as apex planning organization clears out the water related project taken by different agencies.

All the above mentioned plans includes both the structural and non-structural measures were practiced to mitigate flood damage, improved drainage and irrigation in Bangladesh. Embankments, levee, flow regulating structures and other appurtenant structures were operated as a structural measure while flood forecasting and warning, flood proofing, floodplain extend and inundation depth mapping, flood fighting, erosion prediction were practiced as non-structural measures to mitigate the impacts of flood in Bangladesh. The Flood extent and inundation depth mapping are important for appropriate land use planning in flood-prone areas, and optimal exploitation and management of the land and water resources as well as flood inundation management (Rahman M.M. 2015). The sequence of the past flood and water resources management initiatives and studies carried out in Bangladesh from 1964-2018 shown in Fig 2-5

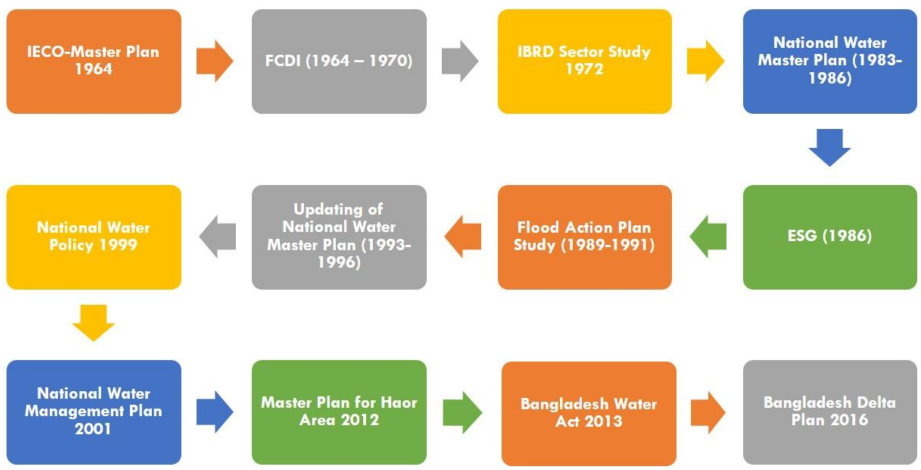


Figure 2-5: Systematic Approaches and Initiatives taken for Flood Control and Water Resource Management in Bangladesh (1964-2018) (Source: CEGIS, 2018)

2.11 Flood Mitigation Measures

2.11.1 Flood and Water Resources Management Interventions

Ministry of Water Resources (MoWR) Government of Bangladesh is the lead ministry plays the vital role in decision making for implementation of flood control and water management measures and interventions. It has almost seven organizations of which five government organizations (BWDB, WARPO, JRC, DHWDB and RRI) and two trusties (IWM and CEGIS) are under its umbrella. BWDB under facilitation of MoWR has implanted WRM projects (both structural and non-structural) for flood and water resource management for reducing the negative impacts of flood and ensure water security for securing peoples' life and livelihoods, property and food etc. The government emphasizes on protecting medium high and medium low lands from floods through implementation, operation and maintenance of the stated number of projects including embankments along with 15 types of interventions since 1959 to 2018. Apart from seven organizations under MoWR, there are other organizations like Bangladesh Inland Water Transport Authority (BIWTA) and National River Conservation Commission (NRCC) of Ministry of Shipping (MoS) execute dredging activities, recover rivers land engulf by industrialist and other powerful leader who execute many interventions for their own interests. One organization that is LGED under the ministry of LGRD who also implement small scale water management project which are less than 1000 ha only.

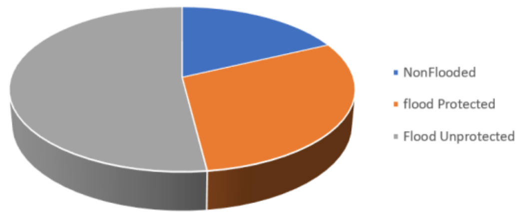


Figure 2-6: Present Flood Status (Hossain, 2003)

2.11.2BWDB

BWDB is the leading organization in water management department and has already implemented 865 projects. It has implemented water management infrastructures and large and medium water management projects in different parts of the country. The average land acquisition for the big or large project is more than 15000 ha and medium projects requires land acquisition in between the range of more than1000-15000 ha. The pie diagram in Fig 2-6 shows the status of flood protected, flood unprotected and non- flooded areas in Bangladesh.

The projects of BWDB consists of 15 types of interventions within the period of 1959 to 2018 includes: 1) Reservoir Constructed 2 Nos. (Kaptai Lake: Capacity: 647.70 crore cubic metre water), Mohamaya Lake: Capacity: 7.28 crore cubic metre water); 2) Barrage Constructed 4 Nos. (Teesta, Manu, Buri Teesta and Tangon), 3) Rubber Dam Constructed 5 Nos. (Pekua, Mohamaya, Palakata, Kohua and Baggujara); 4) River Bank Protection 1229 km; 5) Spur Constructed 221 Nos; 6) Flood Wall Constructed 10 km. 7) Embankment Constructed 15886 km [Coastal Embankment (139 Nos. Polders) - 5676 km, Submersible Embankment (99 Nos. Haor/Haor Sub Project) - 3073 km., Other Flood Control Embankment: 7137 km); 8) Irrigation Canal Dyke Constructed 3612 km; 9) Irrigation Canal Excavated 5355 km; 10) Drainage Canal Excavated 4500 Km; 11) Water Control Structures 15355 Nos; 12) Pump House Built 23 Nos. 13) Closure Constructed 1401 Nos; 14) Bridge/Culvert Constructed 5705 No; 15) River Dredging & Re-excavation of river, khals and water bodies of 1388 Km.

2.11.3 LGED

Local Government Engineering Department (LGED) under the Ministry of Local Government, Rural Development and Co-operatives (LGRD), implemented many small scale water and flood management projects less than or equal to 1000 ha all over the country. . These projects consists of construction of marginal dykes, small cross dams, small water control structures, rubber dams, drainage canal re-excavation, construction of water retention structures etc. for flow augmentation. These structures control flood and its peak in a small scale and facilitate participatory water resources management and improve drainage to reduce local flooding ultimately. All their projects are being implemented in close participation of the local stakeholders.

2.11.4 BIWTA

Bangladesh Inland Water Transport Authority (BIWTA) under the Ministry of Shipping (MoS) maintains the river navigability of Class I, Class II and Class III routes mainly the main rivers and regional rivers through capital and maintenance dredging and manual re-excavation. This dredging and re-excavation works shown in Figure 2-7 in fact increase the conveyances capacity and water depth of water resources system which ultimately facilitate quicker passage of the flood water, reduce the flood peak and reduce the water inundation during flood season. On the other hand dredging also maintains the river navigability during dry season.

The country has about 24,000 km. of rivers, streams and canals that together cover about 7% of the country's surface. Most part of the country is linked by a complex network of waterways which reaches its extensive size in the monsoon period. Out of 24,000 km. of rivers, streams and canals only about 5,968 km is navigable by mechanized vessels during monsoon which shrinks to about 3,865km in dry period. The authority performs statutory functions of development, maintenance and regulatory nature. Presently BIWTA is preparing the River Dredging Master Plan which will ultimately improve the water flowing capacity and available depth of all the major, minor and small rivers of the country.

Figure 2-7: Maintenance dredging of the main River System as routine activities of BIWTA for maintaining the river navigability at critical location (Source: Google)

2.12 Non-Structural Measures

Non-structural measures are soft measures, mostly knowledge based and participatory measures are being practiced by all the water management organizations. In spite of all the structural activities, it was found that the people living in the medium high and medium low lands are not immune to flooding during moderate to extreme flood events. Government considers the minimizing flood loss where non-structural means is also very important and effective as well. Various non-structural measures are being taken all over the world. The non-structural measures are i) flood and erosion prediction and its proper disseminations involving local people.; ii) campaign and awareness building among local stakeholders on flood fighting; iii) flood inundation and hazard mapping; iv) land use planning and land use mapping; and v) participatory community flood risk assessment.

2.12.1 Flood Forecasting and Warning Centre (FFWC)

Early warning on flood can save lives, and properties. Flood Forecasting and Warning Centre (FFWC) of BWDB established in 1972 with 10 flood monitoring stations on the major river systems. After disastrous floods of 1987 and 1988, the government realized the importance of FFWC and took steps to modernize the system. New FFWC model was developed on the basis of Mike-II hydrodynamic model of DHI and flood-monitoring stations were increased up to 30 in 1996. In 1998 flood, FFWC was found to be very useful providing the early warning and information on the flood. With the experience of 1998 flood, the government decided to improve it further monitoring stations to cover all the flood prone areas of the country under real time flood monitoring. A project was under taken in year 2000 to improve the FFWC further in a better scale. Now it covers the entire country with 85 flood monitoring stations and provides real time flood information with early warning for lead-time of 24 and 48 hours. Currently, FFWC is helping the government, the disaster managers and the communities living in the flood prone areas in matters of flood preparedness, preparation of emergency mitigation plan, agricultural planning and rehabilitations.

2.12.2 CFIS Projects of CEGIS

CEGIS developed the Community Based Flood Information and Dissemination System (CFIS) merging scientific and indigenous technical knowledge (ITK) to disseminate forecasted flood level information by FFWC in the main river system to local level. The increase or decrease of flood level at farmers house level from the FFWC flood prediction was estimated establishing correlation and transmitted these level from Dhaka to local level using mobile phone to the local flood inspector who hoisted the number of white or red flag. Red flag indicates rise of water level at that point while white one indicates the fall of water level. Each flag defines six inches of water rise and water falls.

Local farmers and others stakeholders were trained about the flag hoisting and its significance of rise and fall of water level for one day before so that they could take appropriate measures against the flood to reduce the damage of their properties and assets. This system was tested in pilot scale in two upazillas Nagarpur of Tangail and Daulatpur of Manikganj districts found to provide satisfactory results. Local people appreciated this initiatives as they got benefits of the concept but yet to apply in bigger scale district or country level.

2.13 Flood Inundation Map

Flood inundation map shows the flooding area with depths both spatially and temporally to a basin scale, country scale and also in project scale. There are two conceptual methods for preparing the flood inundation maps are described as below:

a) Using HEC-RAS

The present research has been carried out to develop inundation maps of Harirampur which is assumed to be flooded by embankment breaching and over topping of the riverine flood of the Padma River. The study conducted was based upon a combined one and two dimensional model (1D/2D Coupled) which needs cooperation of GIS and HEC-GeoRAS. The later twos help to form appropriate topographic data and channel cross sections. In HEC-RAS, boundary conditions for upstream and downstream are defined by discharge and water level for running the 1D river, while discharge data was used in upstream side and rating curve was also used in downstream portion for 2D floodplain.

After boundary condition setup, the model calibration and validation are performed using known hydrological data. For floodplain calibration we used about 1% discharge flowing through the channel and only when the channel discharge is more than bank full discharge. However, calibration and validation showed result much closer to the actual scenario. Flood inundation map are generated using RAS Mapper and calculated in GIS by exporting data from HEC-RAS to GIS. The average levee height was about 2m which showed significant amount of resistance against flood. Later, the analysis of flood pattern helped to understand the seasonal growth of flood. Thus, ending of the study may help in planning and management of flood plain area of the Padma River to mitigate future probable disaster through technical approach. Findings of the study may also help to determine suitability of building flood control structure like embankment, detention ponds for prevention purposes (Islam at el. 2016).

b) Using MODIS Image

The detection of the spatial-temporal extent of inundation resulting from the floods caused in Harirampur could be studied using time-series MODIS surface reflectance data. Flood inundation maps were developed from vegetation and land water surface indices derived using surface reflectance. The inundation map developed (using MODIS data was compared with a corresponding RADARSAT image, where both images refer to the satellite-based remote-sensing data. This estimation showed a strong correlation with the inundation area derived from the RADARSAT products (coefficient of determination of R^2: 0.96). It is possible to study flood dynamics by assessing inundation and recession patterns and to perform flood assessments similar to the high-resolution (50 m) microwave satellite, RADARSAT-based flood assessments using products derived from MODIS 500 m imagery.) MODIS has advantages over microwave satellite because it has a high observational frequency and these data are available free of cost. It is concluded that this is a useful method to assess the extent of the temporal and spatial floods in Bangladesh. Typical flood inundation extent map of Bangladesh based on 24hr forecast produced by FFWC, BWDB valid for 2nd August 2016 as shown in Figure 2-8.

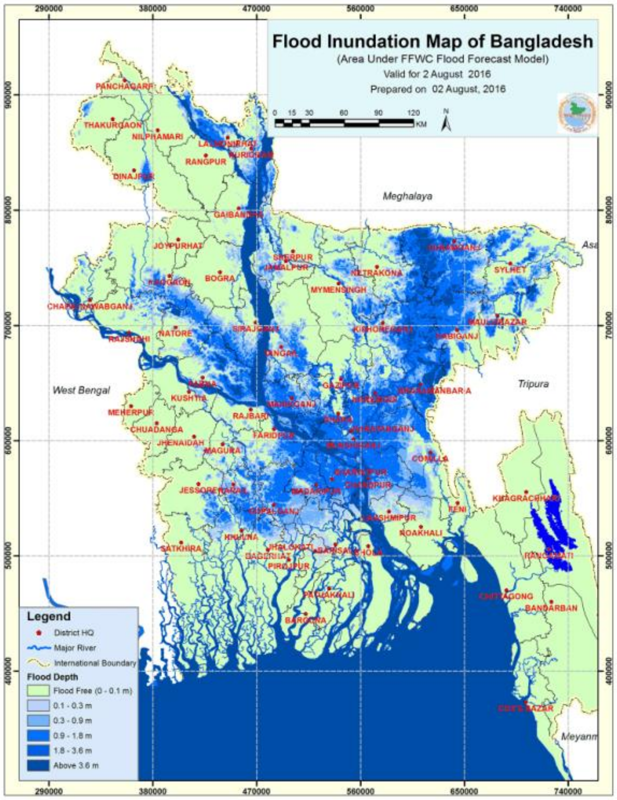


Figure 2-8: Flood Inundation Map of Bangladesh (24hr Forecast Based on 02 August 2016)

2.14 Embankment Breaching and Overtopping

Embankment breaching and overtopping are very common phenomenon occurred with the flood control embankment in the wet season either naturally or due to anthological activities. There are many causes of embankment failure which allows flood water to enter into the protected areas are a) river erosion; b) breaching; c) overtopping; d) public cut; d) protection works; e) encroachment by dwellings, f) wave action and g) faulty instalment of pipe sluices. However, the study is very much focused to embankment breaching and overtopping which allows flood water enters into the protected areas so detail description of causes and reasons of embankment breaching and overtopping are presented as follows:

Embankment breaching: Breach of a flood embankment occurs when water flows over or through the embankment at such a rate that the embankment material eroded/Washed out and in some occasion a hole/passage created that permits flood water to pass through. It is one of the frequent failure mechanism of flood control embankment constructed along the river bank to control floods. The main causes of embankment breaches are a) exceeding the hydrologic parameters; b) lack of compaction of earth during embankment construction; c) lack of systematic routine and annual maintenances; d) inadequate embankment design; e) presences of ghogs and rat holes and seepage through ghogs and rat holes; f) presence of peat soils and many others. A few pictorial presentation of embankment are given in figure 2-9 as bellows:

Figure 2-9: Breaching of embankments in the real world (source: google).

Embankment Overtopping: Overtopping causes due to flood water spilling over the top of an embankment and enter into country side. It is often a precursor of embankment failure. It is another important mechanism by which flood water enters into the protected area. Overtopping of flood water occurs due to following reasons a) exceeds the hydrologic design parameter such as return period of floods; b) inadequate height of flood embankment; c) inadequate free board; d) effect of river confinement; f) subsidence of embankment due to weak foundation soil and g) height of the embankment reduced due to heavy rain and natural shrinkage over the years. Some pictorial presentation of flood water overtopping the embankment are shown in figure 2-10 as follows.

Figure 2-10: Flood water over tops embankment (source: google).

2.15 Flood Hazards Map

Hazard map highlights areas and negative consequences that are resulted by or vulnerable to a particular type of Flood. Hazard map helps to prevent serious damage and deaths and consequences (Udono and Sah, 2002). Flood hazard mapping is a vital component for appropriate land use and spatial development planning in flood prone areas to take appropriate activities both in agricultures and socio-economic activities to reduce the anticipated damage and loss due to flood. It creates easily-read, rapidly-accessible charts and maps which facilitate the administrators and planners to identify areas of risk and prioritize their mitigation/response efforts as a non-structural measure. Geographic Information Systems (GIS) are frequently used to produce flood hazard maps. They provide an effective way of assembling information from different maps and digital elevation (Sanyal and Lu, 2004).

Using GIS, flooding extent is normally assessed by comparing local elevations with extreme water levels. Flood hazard maps can be developed using land cover, elevation, physiographic and geological features and drainage network data. Flood frequency and flood depth can be used as hydraulic components. Hazard index has to be assigned according to inundation depth. But other factors such as frequency of flood, duration of flood, etc. should also be considered (Islam and Sado, 2000). In order to understand the flooding and flood management suitable for spatial and temporal flooding, it is better to look into the land types that will be helpful to delineate hazard categories (Hossain, 2013). These land type classification was almost similar to MPO land type classification only small change in F0 land type of MPO considered 0 to 30 cm inundation whereas present land type Flood Free(FF) considered no inundation and other land types are consistence with this land classification these are:

i. High land (Flood Free), FF: land which is normally flood free and not inundated in any depth during the flood season.

ii. Medium highland, F_1: land which is normally flooded 0 to 90 cm deep during the flood season

iii. Medium lowland, F_2: land is normally flooded between 90 cm and 180 cm deep during the flood season;

iv. Lowland, F_3: land which is normally flooded between 180 cm and 360 cm in the flood season

v. Very lowland, F_4: land which is normally flooded more than 360 cm during the flood season

2.16 Use of Flood Hazard Map

The flood hazard map delineates the type and scale of hazards and its negative consequences created by flood due to breaching and overtopping of flood control embankment along the bank of the mighty river. Bangladesh is a land of rivers and all the socio-economic infrastructures, growth centers and business centers are being developed in the flood protected project areas and sometimes at the bank the river. Following are the probable use of flood hazards maps:

a) Flood Hazard Map provides the average depth of water in the protected area generated due to breaching and overtopping of flood control embankment for proper fixing of plinth level of any infrastructures so that it will not be affected by flood water inundation.

b) This map will identify erosion vulnerable locations, its scale and probability. This erosion information can be utilized for planning, development and protection of wealth, infrastructure damage and important resources;

c) Flood water damages communication infrastructures (earthen and metaled road) and hinders regular communication. So using the flood hazard map, top level of the communication infrastructures can be fixed and be implemented;

d) Flood risk zones can be defined under embankment breaching and overtopping condition. So business oriented people can utilize the information from map to develop business center even in the areas considering required and adequate measure ;

e) Culture fisheries are being practiced in ponds within the projects. The flood inundation and hazard map will provide the scale of damage to be occurred and sufficient measures could be taken to protect the fisheries cultured in the fish ghers/fish ponds using the information.

f) Ground water are being extracted using tube wells and a sufficient height is to be maintained for tube well platform so that tube well may not go under water due to flood flow through embankment breaching. Tube well platform level can be fixed at different spatial location using information of flood depth inundation and flood hazard map

g) Similarly, minimum height of plinth level of the commonly used latrine and house hold latrine in the rural areas are also been fixed using flood hazard maps**.**

Chapter 3: Literature Review

3.1 Introduction

Bangladesh is a lower riparian deltaic country consists of flat flood plains and it is a unique due to its hydro-morphological complex dynamics, flooding and sedimentation process. Anthropogenic and man-made activities and interventions for flood mitigation makes complicated the natural process of flooding and inundation. Therefore, it has been explored the knowledge and studies carried out over the years. Many national and international studies/researches carried out in the past, particularly concerning, embankment failure, the floodplain inundation mapping, flood hazard mapping, flood forecasting and to delineate both structural and non-structural measures for efficient flood management. Interesting researches compatible with the present thesis topic have been explored, reviewed and summarized for improving conceptual understanding about flood inundation, problem analysis, its consequences, hazard mapping and mitigation measures practiced over the years and to generate location specific new ideas and problem solving mitigation measures.

All these studies and researches described in this chapter, enables the author to develop his knowledge on Floodplain Inundation Map and Hazard Map from flooding and determined results by model due to breaching and overtopping of the embankment. These above mentioned maps prepared as an outcome of the study and presented in the relevant chapters. Efforts also have been made for making authors understanding through reviewing thesis reports, journals, books, tools, user manuals and a summary of study finding are presented in the sections as below. All the studies reviewed classified in two classes: a) national studies and b) international studies.

3.2 Studies on Hazard Mapping

3.2.1 National Studies

a) Amanullah (1989) conducted a study on different type's failure of flood control embankments in water development project of BWDB. In his study, he explored the type of failure occurred in water projects in Bangladesh, the reasons of embankment failure and probable mitigation measures to control the failure on the basis analyzing the different cases. There are many causes of embankment failure which allows flood water to enter into the protected areas are a) river erosion; b) breaching; c) overtopping; d) public cut; d) protection works; e) encroachment by dwellings, f) wave action and g) faulty instalment of pipe sluices. However, the study was focused to embankment breaching and overtopping which allows flood water entering into the protected areas and for enhancing the knowledge of the author on flood water overtopping and breaching of the embankment. The detail description of causes and reasons of embankment breaching and overtopping and suggested measures are presented in the chapter 4 of this report.

b) Tazin (2018) explained the development of flood hazard map in Dharla River floodplain, located in the North-West Zone (NW) of Bangladesh using 1D/2D coupled hydrodynamic model. HEC-RAS in connection with HEC-GeoRAS were used to develop maps from the hydrodynamic model results. Automated GIS processing procedures in HEC-Geo RAS helped to provide a useful and expeditious method for repetitive hydraulic model development during analysis of the Dharla River floodplain.

After determining reach length, stream centerline, main channel bank, flow path lines and cross sections using HEC-GeoRAS, data were imported into HEC-RAS using a data exchange format. Model results on water depth and extant were processed for delineation of flood inundation map and hazard map. The model was calibrated and verified using time series data for 2013 and 2014 respectively with observed water level data using Manning's roughness coefficient (n). The study showed that the methodology for river flood analysis using 1D/2D coupled hydrodynamic model is generic and could be applied to similar geographical conditions of flashy Rivers. According to the study, 23.8% and 34 % of total study area were inundated by flood in 2017 and 1998 respectively. From the hazard mapping, it was found that out of ten upazilas such as Lalmonirhat Sadar, Phulbari and Kurigram Sadar were the most vulnerable and Chilmari, Bhurungamari and Kaliganj upazilas which are the outermost upazilas of Dharla River floodplain located in the zone were less susceptible to flooding. Considering agriculture land use pattern, Boro - Fallow -T.aman was found to be the most vulnerable crop and Rabi Crop - B.Aus - Fallow was the less vulnerable crop to the flood of 2017 and 1998 in the study area.

The study also concluded that 1D/2D coupling model with HEC-RAS could determine mainly the spatial distribution of the flood inundation in the Dharala River flood plain. The author was also attempted to identify the hazards of each upazillas as a results of such flood inundation in different parts of the Dharala River catchment. Furthermore, what were the hazards generated due to such flood water inundation in the flashy river catchments were also assessed.

c) NHC FS Study (2013) in their Flood and River Erosion Mitigation Project(FREMIP): This study summarized the hydrological conditions in the 13 sub-reaches along the main rivers of Bangladesh and provided a detailed understanding about inundation patterns in three priority sub-reaches that were identified during the project's pre-feasibility assessment phase (NHC, 2012). The three priority projects were JRB-1 on the right bank of Jamuna River, JLB-2 on the left bank of Jamuna River and PLB-1 on the left bank of the Padma River. The projects involved river bank stabilization measures and other flood mitigation works, including flood control embankments. Hydraulic modelling was carried out to assess the magnitude and extent of flooding in these project areas under "without project" and "with project" conditions. This analysis was used to estimate the project benefits as well that accrue from improved flood protection. The effect of several flood mitigation alternatives and future flooding scenarios were investigated using a hybrid approach, consisting of hydrodynamic modelling using regional flood models supplemented by interpretation of RADARSAT imagery analysis results.

The study also showed that proposed new embankment in sub-project would increase the F0 and F1 land during an average (2003) flood year. Upgrading river bank protection in JRB-1 near Enayetpur would prevent breaching of the embankment, and would protect 11,772 ha of F0 land from becoming deeply inundated. The existing embankment along the left bank of the Jamuna/Padma River provided some protection against overtopping during moderate and low flood years, but had many openings and was not expected to function effectively during extreme floods. Loss of this embankment due to erosion or breaching would significantly worsen flooding in sub-projects JLB-2 and PLB-1. Raising and upgrading a relatively short (approximately 42 km from Zionpur to Dohar) section of the embankment provided only minor flood protection. The total increase in F0 land was estimated to be

3239 ha for average (2003) flood conditions. This showed that relatively localized embankments could provide only location specific flood protection. The effectiveness of a continuous embankment extending along the left bank from near Zionpur to the Dhaleswari River offtake was also assessed. Three water control structures were represented at key distributary offtakes (Ghior Khal and Dhaleswari River). This embankment significantly reduced flooding inside both JLB-2 and PLB-1 sub-projects. F0 land was increased by 32,274 ha during a moderate (2003) flood condition.

Further studies need to be taken to ensure reliable, effective control structures could be operated on the distributary channels and to assess the impact of these structures on sedimentation processes, ensure water quality and quantity in the distributary channels. The effect of constructing two polders (sub-projects) on the left bank of Padma and on the left bank of Jamuna River was also assessed. The project increased the total F0 land under average flood conditions and as such provided less flood benefit than the long, continuous embankment.

d) Masood (2011) studied flood hazard and risk assessment in mid-eastern part of old Dhaka. An inundation map was prepared for the mid-eastern Dhaka (area 37.16 km^2). This study simulated the results on the basis of Digital Elevation Model (DEM) data from Shuttle Radar Topography Mission (SRTM) and the observed flood level time series data for 32 years (1972-2004). The topography of the project area has been considerably changed due to rapid land-filling by land grabbers, urbanization and other human activities. The collected DEM data was then modified according to the recent satellite image information. The flood inundation simulation was conducted using HEC-RAS model for flood of 100 year return period. Both present natural condition and condition after construction of proposed levee (top elevation ranges from 8.60 m to 9.00 m) have been considered in simulation study. After simulation, it was found that the maximum flood water depth was 7.55 m at the south-eastern part of that area and affected was 50%area by flood. Finally, using simulation model result, a Flood Hazard Map was developed using the software ArcGIS. Moreover, risk map was also prepared for this area by conducting the risk assessment.

e) Bhuiyan (2014) assessed the hazard and vulnerability of riverine flood in Khoksabari union of Sirajganj Town surrounded by rivers the Jamuna, the Bangali and the Karatoa which makes the Union vulnerable to flooding assessed using Remote Sensing (RS) and Geographic Information System (GIS). Flood frequency analysis was done to assess flood inundation for different flood magnitudes. Flood inundation maps were prepared based on DEM and satellite image for different risk elements using ILWIS software. LANDSAT images were downloaded and used to develop land use map in the study area. The land use map was used for mapping of settlement and fishery by using ILWIS software. The vulnerability function was developed for preparing vulnerability maps for settlements and fisheries. A depth-damage relation was established for developing vulnerability function. Present monetary values of settlement and fisheries damage due flood were collected through field survey in the study area.

Vulnerability functions of settlements and fisheries were used to produce raster- based vulnerability maps. It was found that Log Pearson Type III distribution is the best fitted distribution for flood frequency analysis in the study area. In 100-year return period flood, inundation percentage of the total agriculture, settlement, fishery and road areas were 48%, 35%, 53% and 38%, respectively. High land (F_0) of the study area was 55%, which was not much inundated in normal monsoon flood. It was also found vulnerability scaled as low, very low, moderate, high and very high vulnerable settlement areas to be 17, 12, 3.43, 1.03 and 1.35 percent, respectively for flood of 100-year return period. These correspond to a maximum of 20%, 40%, 60%, 80% and more than 80% damage of the respective settlement areas. In 100-year flood, low, very low, moderate, high and very high vulnerable fishery areas were 18, 19, 9, 3 and 4 percent respectively. These correspond to a maximum of 20%, 40%, 60%, 80% and more than 80% damage of fishery areas. The results of his study was useful for future flood damage mitigation planning for other areas.

f) Islam and Sado (2000) assessed flood hazard of the study using NOAA-AVHRR data with administrative boundaries (districts) and physiographic, geological, elevation and drainage network data. Flood frequency and flood water depth were main components for evaluation of flood hazard in the study area. The categories of flood-affected area and flood water depth were estimated using NOAA satellite data. Flood hazard rank assessment was also made on the basis of land cover classification, physiographic divisions, geological divisions, elevation intervals and administrative districts. All these data and maps were developed in digital form and used as a GIS database in other fields.

The study showed that 71% of hazard ranks in the area were the same for the best combination of thematic data whether these had been estimated with regard to flood affected frequency or flood water depth. 75% of the administrative district fell within the same risk zones when estimated using either flood-affected frequency or flood water depth.

Finally, flood risk assessment was made using both flood hazard maps for the administrative boundaries (districts) considering the synergistic effect of flood affected frequency and flood water depth. It was also showed that 7.50% of areas were at very high risk and 16.34% were at high risk. The capital city was also in a high risk area. The study concluded that generated flood hazard and flood risk maps might help the responsible authorities to better comprehend the inundation characteristics of the flood plains, the protection of which is their responsibility. Finally, these types of flood hazard and risk map in digital form could be used as database and shared among the various government and non-government agencies responsible for construction and development of interventions to flood defense.

g) Dewan et al. (2007) illustrated the development of flood hazard and risk maps in Greater Dhaka using geo-informatics. Multi-temporal RADARSAT SAR image and GIS data were employed to delineate flood hazard and risk areas for the 1998 historical flood. Flood frequency and flood depth were estimated from multi-date SAR data and considered as hydrologic parameters for the evaluation of flood hazard using land-cover, geomorphic units and elevation data as thematic components. Flood hazard maps were developed considering the interactive effect of flood frequency and flood water depth concurrently. The study revealed that a major portion of Greater Dhaka was exposed to high to very high hazard zones while a smaller portion (2.72%) was free from the potential flood hazard. The results flood risk map according to administrative division showed that 75.35% of Greater Dhaka was within medium to very high risk areas of which 53.39% of areas were believed to be fully urbanized by the year 2010.

3.2.2 International Studies

a) Pathak et al. (2016) studied on modelling of floodplain inundation for Monument Creek, Colorado, USA. In the study, flood plain map was developed for 11.4 km reach of monument creek at Colorado Springs, Colorado. The study presented the concept and approach for terrain modelling and flood plain mapping. It incorporated the hydraulic modelling using HEC-RAS and terrain modelling using Arc Hydro to create floodplain map. The reach of Colorado Spring was successfully modelled and map was delineated showing the flooded areas along the Monument creek. Flooded areas along the creek were delineated but there were some uncertainties, which was not overlooked. Change was noticed between the topography of the flood plain and digital elevation model, which could because of not containing high-resolution terrain data. It was also found that high-resolution digital data of river geometry would hence require to create an effective terrain models as the accuracy of hydrologic modelling largely depends upon the accuracy of terrain data used in GIS.

Vulnerability assessment of the year 1935 flood event as well as 200-year return period flood magnitude, with the aid of GIS and HEC-RAS in their study, which resulted that the risk to which the city of Colorado Springs is exposed. In the city, the most drainage structures were designed for 100-year return period flood level and the structures, if exposed to higher magnitude flood level, would get affected by flood waters. In the future, with the increasing climate warming and resulting increase in frequency and intensity of rainfall events, it became prudent to model flood plain for future.

c) Mani et al. (2014) studied on flood hazard assessment with multi-parameter approach derived from coupled 1D/2D hydrodynamic model. Hydrodynamic flow modelling was carried out using a coupled 1D/2D hydrodynamic flow model in northern India where an industrial plant was proposed. The model simulated two flooding scenarios, one considering the flooding source at regional/catchment level and another considering all flooding sources at local level. For simulating flooding scenario due to flooding of the upstream catchment, the Probable Maximum Flood (PMF) was routed in the main river and its flooding impact was studied at the plant site, due to local level flooding.

In addition to PMF in the main river, the probable maximum precipitation was also considered at the plant site and breaches in the canals near the plant site. The flood extent, depth, level, duration and maximum flow velocity were computed. Three parameters namely the flood depth, cross product of flood depth, velocity and flood duration were used for assessing the flood hazard. A flood hazard classification scheme was proposed. Flood hazard assessment for flooding due to upstream catchment and study on local scale facilitates on their study the determination of plinth level for the plant site and helps in identifying the flood protection measures.

3.3 Uses of HEC-RAS in Flood Inundation Modelling

3.3.1 National Studies

a) Rouf (2015) conducted research on flood inundation map in a low-lying riverine flood prone area of Sirajganj district. In this study, weather forecast model was coupled with a hydrologic model and resulted hydrodynamic model for predicting floods in Jamuna River at Sirajganj district were used. Weather Research and Forecasting Model (WRF 3.0) was used to predict rainfall over the basin with lead-time of 6 days in the study. At first, hydrological model HECHMS 4.0 was calibrated and validated with discharge at Bahdurabad station of Brahmaputra/Jammuna River which was derived from Global Weather Rainfall Data with Clark's Unit Hydrograph transformation method. Output from the WRF model coupled with hydrologic model HEC-HMS. Before using the model for prediction, the HEC-HMS model with WRF output was calibrated by observed discharge at Bahdurabad station. WRF predicted rainfall for 1st June 2014 to 9th October 2014 to HEC-HMS were introduced and the generated river discharges of sub basin to the HECRAS 4.1.0 hydrodynamic model were used for water profile computations along the Jamuna River.

This hydrodynamic model was again calibrated and validated with observed water level at Bahdurabad station. The output of calibrated and validated hydrodynamic HEC-RAS model was exported to Arc-Map 10.1 where it was visualized as a flood inundation map with the use of the extension of HEC-GeoRAS. These maps developed for each day integrating the Digital Elevation Model (DEM) data of Shuttle Radar Topographic Mission (SRTM) and interpolation of water level height obtained from HEC-RAS output at different cross-sections. Observing these maps, it was found that Sirajganj district suffered the highest inundation in the month of August. On 24 August 2014, Shahjadpur , Ullah Para , Tarash and Chauhali thanas were completely inundated with flood water and other thanas named Kamarkhand and Royganj were inundated partially. Inundation map prepared by HEC-GeoRAS, was mainly done by the water occupied channel area as areal extent due to rainfall. Flood due to overtopping was considered in this study, flooding due to breaching of embankment or other reasons was not considered in her study.

b) Rahman (2015) studied to develop flood extent maps and inundation maps of the Jamuna River. The Jamuna River is most vulnerable to river flood in Bangladesh. His study also dealt with flood pattern change with time and impact of embankment on flood inundation area. One dimensional hydraulic model HEC-RAS with HEC-GeoRAS interface in co-ordination with ArcView was applied for the analysis. Collected bathymetric river grid was merged with the topographic DEM to produce the complete DEM of the river. Using the complete DEM, stream center line, banks, flow paths and cross sections data prepared in HEC-GeoRAS were imported.

After boundary condition setup, the model was calibrated and validated using known hydrological data collected from BWDB. The coefficient of determination (R^2) was found as 0.985, 0.977, 0.821 and 0.811 for steady calibration, steady validation, unsteady calibration and unsteady validation respectively. It was also found the NSE greater than 0.60 for both calibration and validation. Flood inundation and flood hazard map were generated using post-processing of HEC-GeoRAS. It was found in his study that the percentages of area inundated by the flood of 2, 5, 10, 25, 50 and 100-year return periods were 38.28, 46.10, 51.14, 54.63, 56.89 and 59.19% respectively. The result showed that flooding area had water depth between 1.2 m to 3.6m. The assessment of flood inundated area showed that 41.99% and 30.83% area were of high hazard and very high hazard respectively for the 100-year return period flood. It was also found that, for the 100 year return period, if levee elevation is raised up to 2.13 m from existing crest elevation, then flood inundation land area decreased from 59.19% to 40%, no land would be inundated, if the levee elevation raised up to 2.56 m.

c) Hossain (2015) developed 5 (five) days forecasted flood inundation map and hydrograph at house level flood information at Rowmari Upazilla of Kurigram district. This study area is surrounded by the mighty Brahmaputra River and flashy Jinjiram River. In this study, a weather prediction model (WRF) was coupled with a hydrologic model (HEC-HMS) and a hydrodynamic model (HEC-RAS) for predicting floods at Rowmari upazilla of Kurigram district. WRF 3.2 weather model was configured and used to predict rainfall over the basin 120 hours into future.

Output of the weather model was incorporated with calibrated and validated hydrologic model HEC-HMS 4.0 and simulated every day during monsoon to forecast discharge at Bahadurabad. Three mathematical relations were developed between Bahadurabad stations to other boundary of hydrodynamic model for forecasting boundary generation. Then hydrodynamic model was simulated every day using forecasted boundary to generate flood inundation map and forecast hydrograph at Rowmari upazilla of Kurigram. It was found that the estimated NSE value for the calibration and validation period is 0.85 and 0.82. The hydrodynamic Model (HEC-RAS) performance was found during calibration and validation period in terms of R^2 and NSE against observed water level data to nearly 1. The Manning's roughness coefficient (n) and the coefficient of expansion/contraction (k) were key parameters in his study to calibrate of HEC-RAS model. In his study, analysis of forecast performance indicated that the forecast for the first 3 (three) days were good and next two days were average to poor according to BWDB guideline. It was concluded that the developed flood forecasting system is capable of predicting the inundated area of Rowmari upazilla during a monsoon season.

d) Das, Khan and others (2018) conducted the study using HEC-RAS 1D/2D coupled model illustrated the development of inundation maps of the Surma and the Kushiyara River. For this purpose, one and two dimensional HEC-RAS models were used. Boundary conditions were defined in the model and the models were calibrated and validated by the collected data from Bangladesh Water Development Board (BWDB). The calibration and validation showed much closer result to the actual scenario. The inundation maps under different scenarios by changing the discharges were developed using RAS mapper. Levee/embankment was constructed in HEC-RAS 2D model.

The study showed that average embankment height of 1.8 m was provided sufficient resistance against flooding. Seasonal growth of flood could be understood by analyzing flood pattern. It might help in planning and management of flood plain area of the Surma and Kusiyara Rivers to mitigate future probable disaster through technical approach and to determine suitability of building flood control structure like embankment, detention ponds for prevention purposes.

3.3.2 International Studies

a) Betsholtz and Nordlöf (2017) studied that hydraulic models can be useful to predict the consequences of flood. Under this project, three hydraulic models were developed using the software HEC-RAS, and compared through a case study on Höje river catchment. The models include (i) 1D model, where river and floodplain flow was modelled in 1D, (ii) a coupled 1D/2D model, where river flow was modelled in 1D and floodplain flow was modelled in 2D, and (iii) a pure 2D model, where river and floodplain flow was modelled in 2D. Important differences were between data requirements, pre-processing, model set-up and results were highlighted and summarized and a rough guide that might be used when deciding the appropriate type of model for a project, was presented.

In addition to that, the sub-grid technique generally used in 2D HEC-RAS modelling was studied by investigating the influence of computational mesh structure and coupling between 1D and 2D model areas. The results showed that all three models could successfully reproduced a historic flooding event. The 2D and 1D/2Ds model could also provide more detailed information regarding flood propagation and velocities on the floodplain. The results from the 2D mesh analysis showed that model result was very sensitive to mesh alignment along barriers. In rural floodplains with clear barriers, computational cell alignment was more important than computational cell size. Regarding 1D/2D model, the results showed that the parameters describing the coupling between the 1D and 2D model domain had large impact on model results.

b) Chow et al. (1988) presented a straight forward approach for processing output of the HEC-RAS hydraulic model, to enable two and three dimensional floodplain mapping and analysis in the ArcView geographic information system. The methodology was applied to a reach of Waller Creek, located in Austin, Texas. A plan metric floodplain view was developed using digital ortho-photography as a base map. Moreover, synthesized a digital terrain model from HEC-RAS cross-sectional coordinate data and a digital elevation model of the study area. Finally, the resulting surface model was created, which provided a good representation of the general landscape and contains additional detail within the stream channel. Overall, the results of the research indicated GIS as an effective tools for floodplain mapping and analysis.

c) Kalra and Ahmad (2012) studied two dimensional flow routing capabilities of HEC-RAS for flood inundation mapping in lower region of Brazo River watershed subjected to frequent flooding. River reach length of 20 km located at Richmond, Texas was considered. Detailed underlying terrain information available from DEM of 1/9-arc second resolution was used to generate the 2D flow area and flow geometrics. Stream flow data available from gauging station USGS08114000 were used for the full unsteady flow hydraulic modelling along the reach. Developed hydraulic model was calibrated based on the manning's roughness coefficient for the river reach by comparison with the downstream rating curve. Water surface elevation and velocity distribution obtained after 2D hydraulic simulation were used to determine the extent of flooding. For this, RAS mapper's capabilities of inundation mapping in HEC-RAS itself were used. Mapping of the flooded areas based on inflow hydrograph on each time step were done in RAS mapper, which provided the spatial distribution of flow. The results from their study could be used for flood management as well as for making land use and infrastructure development decisions.

d) Ahmad et al. (2010) executed out a study by integrating hydrological models with GIS to estimate the flood zone of Nullah Lai in Rawalpindi, Islamabad, Pakistan. HEC-RAS and HEC-GeoRAS hydrological models were used to delineate the areas vulnerable to flood at different discharge values. A topographic survey of fine resolution of the target area (Kattarian to Gawalmandi Bridges) was used to generate the DEM of the area. Krigging method was used to interpolate the elevation data. GIS technology was also used to delineate the variation of topography and to find out the inundation depths of water at various locations in the study area.

Inundation area estimated at the discharge value of 3000 m^3/sec is 3.4 km^2 out of which 2.96 km^2 was occupied under the inundation depth from 1 to 5 meters. It was also found that maximum inundation depth can go up to 20 meters for this discharge value. Output of their study using HEC-RAS showed that water inundated areas and water inundation depths are in close approximation with survey based inundation results obtained by JICA. So their study showed that the integrated modelling approach used in this study worked well in order to delineate areas vulnerable to flood with a good estimation of inundation depths at a specific discharge value.

e) Moore (2011) on his study created an atlas of steady inundation maps for communities in Iowa, USA which showed a high risk of flooding. A high-resolution coupled one-dimensional/two-dimensional hydrodynamic model of Charles City, Iowa was developed in his study. Channel geometry from bathymetric surveys and surface topography from LiDAR were combined to create the integrated Digital Elevation Model (DEM) used in numerical simulations. Coupled one and two dimensional models were used to simulate flood events. The river channel and structures were modelled one-dimensionally and the floodplain was modelled two-dimensionally. Spatially distributed roughness parameters were estimated using the 2001 National Land Cover Dataset. Simulations were performed at a number of mesh resolutions and the results were used to investigate the effectiveness of re-sampling simulation results using higher- resolution DEMs. The effect of removing buildings from the computational mesh was also investigated.

f) Patel et al. (2017) carried out a study on assessment of flood inundation mapping of Surat city, India by coupled 1D/2D hydrodynamic modelling. Surat city of India, situated 100 km downstream of Ukai Dam and 19.4 km upstream from the mouth of River Tapi, experienced the largest flood in 2006. The peak discharge of about 25,770 m^3/s released from the Ukai Dam was responsible for a flood disaster. Two hundred ninety-nine cross sections, two hydraulic structures and five major bridges across the river were considered for 1D modelling, whereas a topographic map at 0.5 m contour interval was used to produce a 5 m grid and SRTM (30 and 90 m) grid was considered for Surat and the Lower Tapi Basin. Tidal level at the river mouth (u/s) and the release from the Ukai Dam (d/s) during 2006 flood were considered as the downstream and upstream boundaries, respectively.

The model simulation was conducted under the unsteady flow condition and validated for the year 2006. The simulated result showed that 9th August, 2006 was the worst day in terms of flooding for Surat city and a maximum within the range of 75–77% area were under inundation. Out of seven zones, the west zone had the deepest flood and inundated depth under 4–5 m. Furthermore, inundation was generated under the bank protection work (i.e., levees, retaining wall) constructed after the 2006 flood. The simulated results showed that the major zones were safe against the inundation under 14,430 m^3/s water releases from Ukai Dam except for the west zone. In their study, the 2D model capability of new HEC-RAS 5 for flood inundation mapping and management studies was observed.

3.4 Benefits of Reviewing the above Mentioned Studies

Reviewing all the above mentioned national and international studies under two different thematic objectives of assessments such as studies on hazard mapping and uses of HEC-RAS in flood plain inundation modelling enables author to gain knowledge, clear the concepts on 1D/2D coupled hydrodynamic modelling and conducted the study in a sequential way satisfactorily.

Chapter 4: Study Area Baseline Setting

4.1 Introduction

This chapter presents baseline of study area on social and environmental issues/resources, flood dynamics i.e. flow regime, water resources systems, flood dynamics and Hydro- morphology (river bank line change, erosion and water resources), meteorology, soil and agricultural practices, forest resources, changing of agricultural practices, cropping pattern and fisheries resources of Harirampur. Riverine flood and River bank erosion are severe problems and have both direct and indirect effects on human life, livelihoods, environment and socio-economy of the people study area. The present research investigated flood inundation and extent, flood hazard caused by breaching and overtopping of embankment. Furthermore impacts of embankment breaching and overtopping on socio-economic livelihood and vulnerability on local people due to land loss and its environmental consequences in the study area was also investigated.

4.2 Geographical Location and Socio-Economic Aspects

Harirampur, the largest upazilla of Manikganj in respect of area, came into existence as a thana in 1845 and was upgraded to upazila in 1983. In the past there lived one Hare Ram Shaha, very rich and influential man of his time who tried to establish a police station in this area to maintain law and order situation. It is generally believed that the upazilla might have originated its name from the name of Hare Ram Shaha. The upazilla occupies an area of 243.30 km^2 located between 23^{0}38'and 23^{0}48'north latitudes and 89^{0}50' and 90^{0}03' east longitudes. It is bounded on the north by Shibalaya upazilla, Manikganj Sadar upazilla and Ghior upazilla, east by Nawabganj upazlla and Dohar upazilla of Dhaka district and Manikganj Sadar upazila, south by the river Padma, Char Bhadrasan upazilla and Faridpur Sadar upazilla of Faridpur district and west by Faridpur Sadar upazilla and Goalanda upazilla of Rajbari district and Shibalaya upazilla *(*Population and Housing Census.2011)

4.2.1 Demography

There are 13 unions (3 unions are within the char of Padma River and 10 unions are in main lands) of this upazila namely: Azimnagar, Balla, Balara, Boyra, Chala, Dhulsura, Gala, Gopinathpur, Harukandi, Kanchanpur, Lesraganj, Ramkrishnapur, Sutalary and 214 mouzas and 250 villages . According to Population and Housing Census (2011), the total upazila population is 1, 39,318 of which 65815 are males and 73503 are females. The average population of each union, mauza and village are 10717, 651 and 557 respectively. The literacy rate in 2011 was 48.4% for both sex, 49.7% for male and 47.2% for female.

4.2.2 Drinking Water and Sanitation

As per Population and Housing Census (2011), about 96.7% of household have drinking water facility from shallow tube-well, 0.2% from tap water and the remaining 3.1% household get water from other sources. In respect of sanitation, 57.8% household use sanitary latrine, 39.2% non-sanitary latrine and remaining 3.0% have no toilet and latrine facility.

4.2.3 Access to Electricity, Road Communication and Transport:

According to Population and Housing Census (2011), all unions of the upazilla have brought under electricity connection by the Rural Electrification Board (REB) Program. A total of 48.7%

household have electricity connection in the entire upazilla in 2011 as against 26.3% in 2001. In respect of communication and transportation, Palanquin, house carriage, bullock cart and Gaina boats are the traditional water transports found in the rural areas of Manikganj district. These means of transports are either extinct or nearly extinct. Now-a-days, the upazilla is connected to the district head-quarters by metaled roads. Bus, Minibus, three wheelers ply over the entire upazilla.

4.3 Environmental Aspects and Issues

There are many environmental aspects and issues are being affected by flood water if it is entered either embankment breaching or embankment overtopping. As it is academic research so the main issues and aspects and their present situation of the resources are presented as below:

4.3.1 Agriculture and its Practices:

The tropical monsoon climatic influences to a great extent to the agricultural practice of the area due to the belonging to the active Ganges floodplain which includes river, chars and young floodplain land adjoining the rivers. The eroded part is very unstable and has been emerging either in the form of sandy char land or being carpeted with sand. The major agricultural crops are paddy, jute, pulses, oil seeds, vegetables, spices, potato and sweet potato. *Aman* covers the largest area followed by Aus and *Boro* respectively (Rahman et al. 2018).

The practiced crop are the Aus (*Oryza sativa*) and Aman (*Oryza sativa*) as the principal food crops in the char areas. Whenever the land only shallowly flooded or water can be kept on the land small channels and cricks by small bounds, farmers grow *Aus* followed by transplanted *Aman (*Figure 4-1). This sort of rice practice is confined in particular small earmarked areas (Rahman et al. 2018).

When flooding depth becomes too deep for transplanted *Aman* or where rapid rise of flood-level may cause crop damages and loss of crops in most of the years; broadcast *Aman*, sometimes mixed with *Aus* are grown. On highland where water cannot be kept on the land only *Aus* paddy is grown followed by dry land crop, Sweet potatoes (*Ipomoea batatas*) at the end of the rainy season. The soils are seasonally flooded, have loamy to silty and silty to silty textures and low soil moisture contents (Rahman et al. 2018).

The sand deposition or sand carpeting due to flood embankment breaching, changes local landform, soil properties, drainage and surface water conditions and ultimately decrease the soil moisture which causes localized drought conditions are the barriers of normal crops production in the char agro-environment.

Figure 4-1: Mustard and Rice Crops in the Agricultural Field in Harirampur (Source: Google)

4.3.2 Fisheries and it activities

The most adverse environmental consequences are on flora, fauna and the most affected sector is fisheries. The amount of fish harvest is gradually going down day by day. The bank erosion and the rise of char land at middle of the river decreased the river depth and also changed the flow pattern of spawning ground of capture fishes. This sedimentation process impacts the river navigation. River depth is decreasing rapidly and number of fish species as well.

Major fishes are available in the Padma river are carps (Rui, Catla, Mrigal, Ghania, Kalbasu, Kalia) Hilsa, shrimp, cat fish (Rita, Boal, Pangas, Silon, Aor, Bacha) and snake head (Shol, Gazar, Taki) fish. Hilsa is the national flagship fish of the country. Several fish breeding grounds exist in the River Padma. Janjira is considered one of the important breeding grounds for carps and cat fishes (about 10km upstream of the main bridge alignment). The location of average collection rate of fry (new born fish) from Janjira is 500kg per year. The Hilsa migrates from the sea to the estuaries and rivers mainly for breeding and feeding. Most fishes breed in the monsoon period. Hilsa migrates through the bridge construction site during March-May (Figure 4-2). It has two major spawning seasons, the peak in September-October with a minor-peak in January-February. Hilsa move in the sea on the surface whereas in the river and other aquatic environment, they move at a depth of 14 to 18 meters, though on a cool or drizzly day they may rise to within 2 metres from the surface.

Figure 4-2: Fishing in the river (Source: Google)

4.3.3 Forestry, Tree plantation and Fruits:

The homestead tree plantation is very common and regular practice in area. Every house and homestead has huge indigenous trees (fruits and non-fruits) around the corridor. These trees disappeared gradually due to land erosion. As the erosion is continuing, the amount of land loss is getting high with the loss of agriculture, forestry and homestead and settlements. According to Population and Housing Census (2011), mango/aam (*Mangifera indica*), banana(*Musa sapientum*), jackfruit (*Artocarpus heterophyllus*), palm(*Borassus flabellifer*),lime (*Citrus decumana*),coconut (*Cocos nucifera*), betelnut (*Areca catechu*),guava(*Psidium guajava*), black berry (*Syzygium cumini*),papaya (*Carica papaya*), tetul (*Tamariandus indica*),peach fruit (*Prunus persica*),lemon(*Citrus carantifolia*),pine apple(*Ananas comosus*),sharifa/sweet hop (*Anona squamosa*),bel/wood apple (*Aegle marmelos*),indian palm (*Zizyphus mauritiana*),date palm (*Phoenix sylvestris*) etc.were found common fruits tree in this area (Figure 4-3).

Figure 4-3: Road Side and Homestead Plantation in the Harirampur upazilla (Field visit during August 2020)

4.4 Meteorology, Water Resources System, Riverine Floods and Erosion

4.4.1 Meteorology

The hot summer, long rainy season and the pleasant spring-cum winter are the main noticeable seasons prevailing in the study area. The highest and the lowest average monthly temperature vary from 35.1°C to 14.2°C. The mean July temperature in the area is between 28°C to 29°C. The humidity varies from 56% to 83%. Monsoonal rains from June to September accounts for 60 to 70 percent of the annual rainfall. The annual average rainfall is 250.8 cm (BMD. 2016, BBS. 2011, Rashid. 1991)

4.4.2 Water Resources System (WRS)

The Padma River is the vital Water Resources System in the study area, therefore, it is very important to understand the Padma river behaviors and dynamics i.e. flood flow, physical features of the river and basin, hydrological situations, historical changes of river channel, flood and sediment flow conditions. Based on the understanding on the river conditions, the hydraulic parameters were delineated for developing the conceptual model.

The prominent rivers in Harirampur are the Padma and Ichamoti rivers. This upazilla has been divided in two parts. BWDB has constructed flood control embankment at one side along the river the Padma. Ichamoti river also passes through the Harirampur and it is one of the oldest river. The major rivers such as the Padma, the Dhaleswari and the Jamuna continuously changes the river courses and caused huge erosion results the change of original course of the river the Ichamoti and its offtakes. Ichamoti has many branches within this upazilla through which the water flows. One flow in between kamarkandi and Ichamoti river at Chowkighata flows towards north and east direction and afterwards it moves towards south through Harukandi, Vatikandi, Ramkrishnapur, Lakhikoal and then moves towards east. Afterwards it moves Azimnagar and besides Sayednagar and falls into the Padma river at Mirzapur. One flow originated from the Ichamoti river and moves towards east meets with 2nd flow at Sutalari. Another flow stream originated from ManikNagar passed through Chatrazitpur, Ragunatpur and Joypur and flow meets with the Padma. This dead river flow portion is now named as the Dalamaraer Beel.

The Padma River is one of the big and major river in Bangladesh which flows in between Shibalay upazilla located in the west whereas Harirampur upazilla located in the south. The Ganges river was being familiarized as Padma in Bangladesh. The Kanchanpur, Ramkrishnapur, Boyra, Laserganj, Azimnagar, Dhulsura, Sutalari, and Harukandi unions are located along the bank of the Padma River. Due to severe erosion, Laserganj, Azimnagar, Dhulsura and Sutalari, land are being washed partly. At present, these unions were being expanded due to sedimentation of the river the Padma. Most of the areas Kanchanpur, Ramkrishnapur, Boyra and Harukandi are being washed out (Figure 4-4) in the river the Padma. The inhabitants of these unions are now lived in different areas of Harirampur.

Figure 4-4: River erosion caused loss of lands along Padma River (Source: google)

4.4.3 Flow Regimes of the major rivers including the Padma River

To model the physical process of the Padma River with flood plains, it is necessary to understand the dynamics of flow regimes of three integrated major river systems all together (the Ganges, the Brahmaputra and the Padma).The average water levels and discharges of the Brahmaputra-Jamuna river system at Bahadurabad, the Ganges-Padma river system at Hardinge Bridge, and the Padma river at Baruia Transit are illustrated in Figure 4-5. This difference between the peaks of two rivers (the Ganges and the Brahmaputra) is explained by the main cause of runoff during the period of rising flood. The Padma River rises together with the Brahmaputra and reaches to the peak almost corresponding with the Ganges.

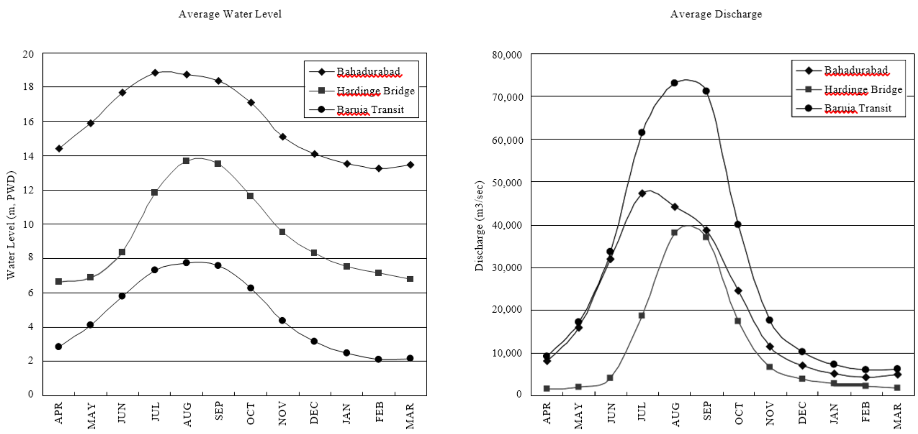


Figure 4-5: Flow Regimes (water levels and discharge) of the Major Rivers (the Ganges, the Brahmaputra and the Padma River) (Source: BBA 2005)

4.4.4 Riverine Flood and its dynamics

The study area consist of the mighty Padma River reach of about 48 km length from Baruria Transit at upstream to Bhagyakul at downstream carried combine flow shown in Figure 4-6 of the Ganges and the Brhmaputra river. The Padma River has bifurcated in two branches when it enters in the Harirampur upazilla and again meets become one river at the end of this Harirampur upzilla. Flooding in the study area occurs due to direct overbank spill from the main rivers, embankment failure, from the internal regional rivers, distributary channels and direct rainfall-runoff accumulation. The significance of each contribution varies from year to year, place to place and within the flood season. Floodplain inundation and drainage in the study area (Figure 4-6) are governed by the interactions and inter-connections between the main rivers, distributaries, *khals* and *beels*. Excess rainwater accumulates first in *beels* until fills up and gradually inundates the agricultural lands and converted as flood. The extent and depth of inundation varies from place to place.

Figure 4-6: The Padma River Flood Carries Huge Flow (source: Field Visit August, 2020)

Riverine flood during wet season carries huge flow in every year and sand deposition takes place within the river conveyance and sand carpeting in protected land if the breach has take place due to flood. Changes of landform, soil properties, drainage and surface conditions ultimately decrease the soil moisture which causes the localized drought conditions are the barriers of normal crops production in the char agro-environment.

Figure 4-7: Study Area and River Systems of Harirampur (Source: BBS 2011)

There are reasonably reliable and long (> 40 years) records of hydrological data are available on the main rivers which provides a basis for estimating the frequency of flood discharges. Table 4-1 summarizes the flood discharge statistics with return period on the River Padma, the River Ganges and the Brahmaputra River using the Gumbel and Log-Pearson Type III distributions (ADB.2013).

Table 4-1: Frequency of Peak Discharges on Three Main Rivers

Return Period	Padma River at Baruria Transit (m^3/s)	Ganges River at Hardinge Bridge (m^3/s)	Brahmaputra River at Bahadurabad (m^3/s)
2-year	94,000	4,970	66,000
10-year	122,000	6,460	85,100
20-year	132,000	6,960	91,400
50-year	143,000	7,570	99,100
100-year	152,000	8,000	104,600

Source: ADB, 2013

4.4.5 Daily Mean Water Levels and Discharges

The daily mean discharge data are available along the Padma at Baruria Transit and water level at Mawa and the off-take of the Arial Khan at Chowdury Hat. A summary of the daily mean discharges is shown in Table 4-2.

Table 4-2: Summary of Daily Mean Discharge of the River Padma at different locations

River	Code	Name of Gauge	Daily Mean Discharge (m^3/sec)		
			Avg. Maximum	Average	Avg. Minimum
Padma	91.9L	Baruria Transit	92,100	29,500	5,080
Padma	93.5L	Mawa	90,000	28,600	4,730

Source: BBA, 2005

A summary of the water level records around the study area is shown in Table 4-3. The records were retrieved on daily mean basis for all the gauges. For the tidal water level gauges, the daily high and low water levels were derived and summarized as well.

Table 4-3: Summary of Water Levels of three major rivers at different locations

River	Code	Name of Place of WL Gauges	Daily Mean Water Level in (m)		Tidal Water Level in (m)	
			Average HWL	Average LWL	Average HWL	Average LWL
Brhamaputra-Jamuna	50.3	Mathura	10.20	3.03	NT	NT
Brhamaputra-Jamuna	50.6	Aricha	9.49	2.56	NT	NT
Ganges-Padma	91.2	Mohendrapur	10.67	3.23	NT	NT

Padma	91.9L	Baruria Transit	8.34	1.92	NT	NT
Padma	91.9R	Goalundo Transit	8.99	2.49	NT	NT
Padma	93.4L	Bhagyakul	6.54	1.28	6.57	1.21
Padma	93.5L	Mawa	6.13	1.12	6.17	1.02

Note: Average HWL/LWL are the average values of the annual maximum/minimum water levels. (Source: BBA. 2005)

4.4.6 Flood Frequency and Duration

The frequency curves of the water levels were prepared for the selected locations i.e. Baruria Transit and Mawa of the Padma River shown in Figure 4-8. The frequency curves for the maximum, the exceeded probabilities of 10%, 50%, and 90%, and the minimum were developed Bangladesh Bridge Authority (BBA, 2005) with a time-step of one day on the basis of the daily mean discharge data.

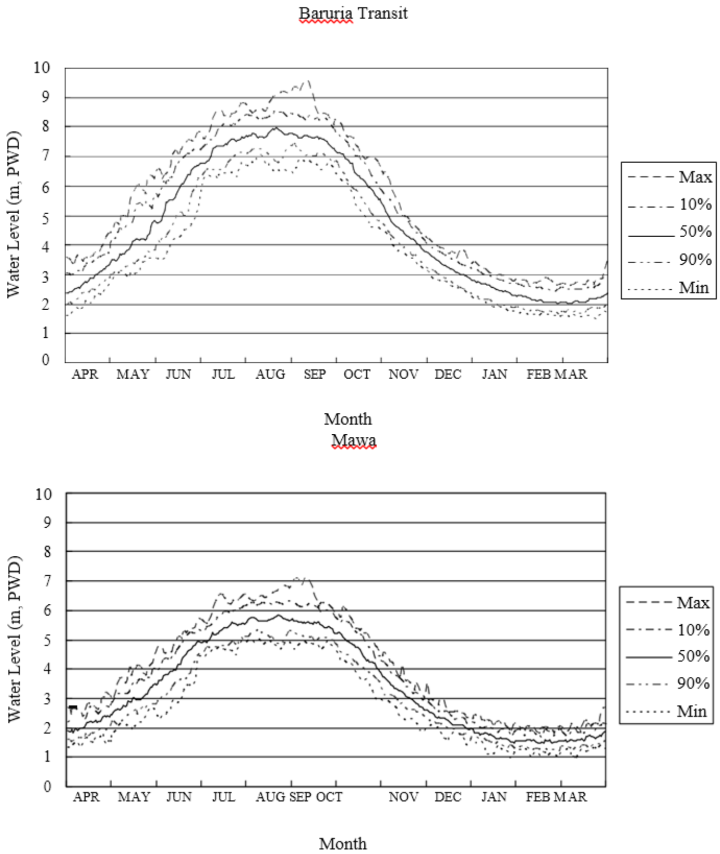


Figure 4-8: Water Level Frequency Curves for Baruria Transit and Mawa stations of the Padma River (Source: BBA. 2005)

4.4.7 River morphology (Bank line movement and Erosion)

The Padma river morphology is dynamically characterized by periodic building of bend which subsequently cut off and filled and then re-eroded shown in Figure 4-9 due to accommodating huge combined flow of the Ganges and the Brahmaputra.

Figure 4-9: Erosion along the Padma River Bank in Harirampur (Source: google)

The channel that was flowing through Harirampur in 2000, was seen bifurcated and a new channel was developed in 2002. Later the bend was cut-off in 2009 and filled and subsequently started to develop the bend again since then (Figure 4-10).

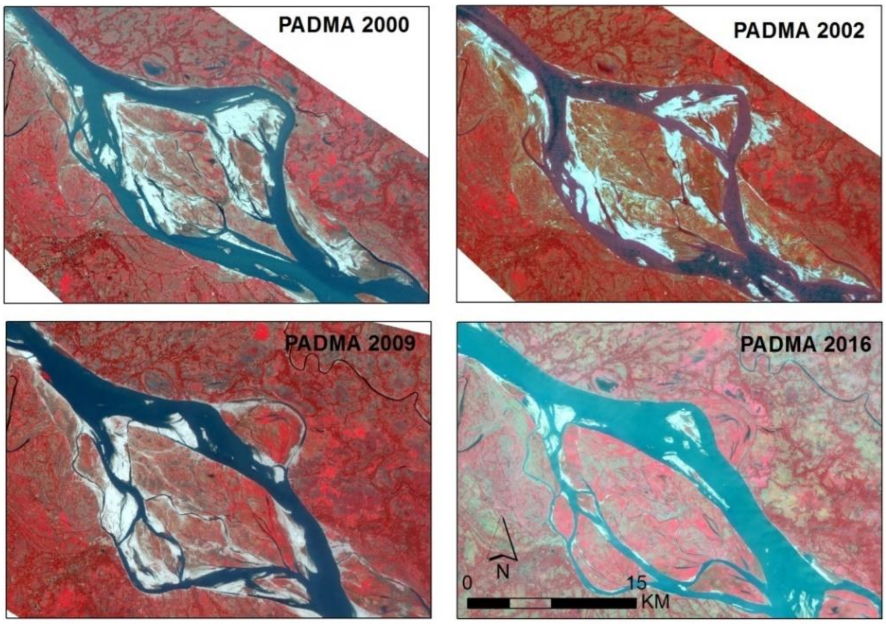


Figure 4-10: Channel Development of the Padma River in Last Two Decades (Source: CEGIS)

The morphological change, the bend has started few years ago. Massive bank erosion of the Padma River has devoured 35625.20 acres of landmass at Harirampur. A major part of the eroded landmass has been emerged as char and on the riverbed with radical changes of the land topography and soil properties. Last two years, riverbank erosion was accelerated and a strong tendency to move east that increased the erosion rates in downstream direction.

4.4.8 FRERMIP Project

Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) consists of three trenches (Trench 1, Trench 2 and Trench 3) will be implementation under the financial assistance of Asian Development Bank (ADB) and the Royel Netherland Embassy (RNE). This project was implemented for sustainable and cost effective erosion risk mitigation measures ensuring people participation. Bangladesh Water Development Board (BWDB) initiated the implementation of Trench 1 component of this project since April, 2018 and will be completed in June 2021.

The Trench 2 project includes erosion mitigation measures in many places along the Jamuna and Padma river bank where Harirampur upazilla is included. The river training works already completed in Trench 1 is 8.8 km river training works by hard materials.Figure 4-11 shows the river training work completed at Harirampur

Figure 4-11: River Training works at Harirampur under FEREMIP project

4.4.9 Lateral Infrastructure (flood control embankment):

Flood Control Embankment has been considered as the lateral infrastructure. There already existed Flood Control Embankment from Kanchanpur to Ramkrishnapur of about 7 km length constructed earlier by BWDB which was already damaged and eroded in different reaches with various scale. The riverbank erosion affected areas are Ramkrishnapur union, Kanchanpur union, Gopinathpur union and Dhulshura union, with huge losses of standing crops, riverbank erosion of the Padma River made 100 families homeless in Harirampur in year 2019. In addition to that houses, roads and other infrastructures in the Manikganj district were devoured by the Padma River creating huge suffering of the flood-hit people.

BWDB official opinioned that this massive erosion in the post-flood period is due to riverbank erosion took alarming turn and devouring vast tract of farming land, houses and some business establishments. BWDB has taken all necessary measures including dumping of sand filled geo bags and maintenances of embankments to check erosion along the banks of the Padma River.

Therefore, BWDB has completed a FS study under the financial assistance of Asian Development Bank (ADB) planned and designed the Flood Control Embankment from Ramkrishnapur to Dhulshura shown in the google image map to be constructed to control flood and erosion. The design section of flood control embankment shown in (Fig-4-12)

Figure 4-12: Existing and Proposed location of Flood Control Embankment/Levee as Lateral Structure

The proposed embankment alignment and its location of starting and ending shown in figure 4-13. However design specification with sufficiently strong and large base width and with provision of berm at country side (Figure 4-14 and Figure 4-15). The average depth of embankment from the ground level to crest level is roughly 6m and above. The embankment crest level varies from 11m to 12m PWD while the ground level varies from 4 to 6 m PWD. The riverside slope is 1:3 without any berm in river side while in country side slope is 1:2 with berm of 5m. The berm has been provide to control seepage and slope failures.

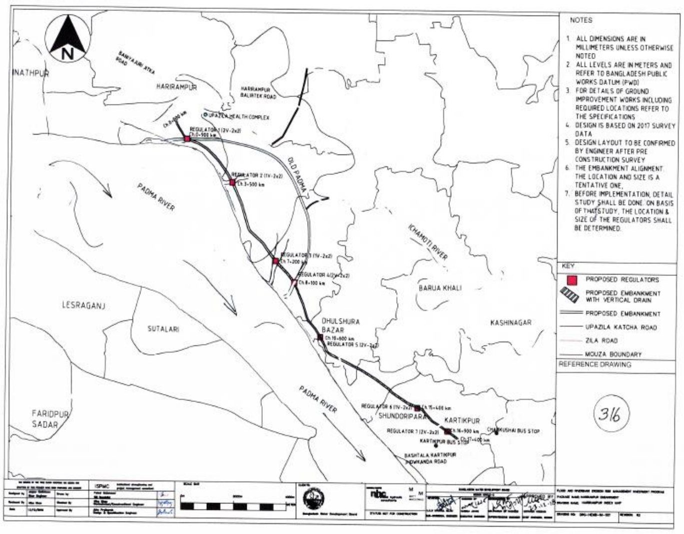


Figure 4-13 Map of BWDB Showing the Location of Embankment (Source: BWDB)

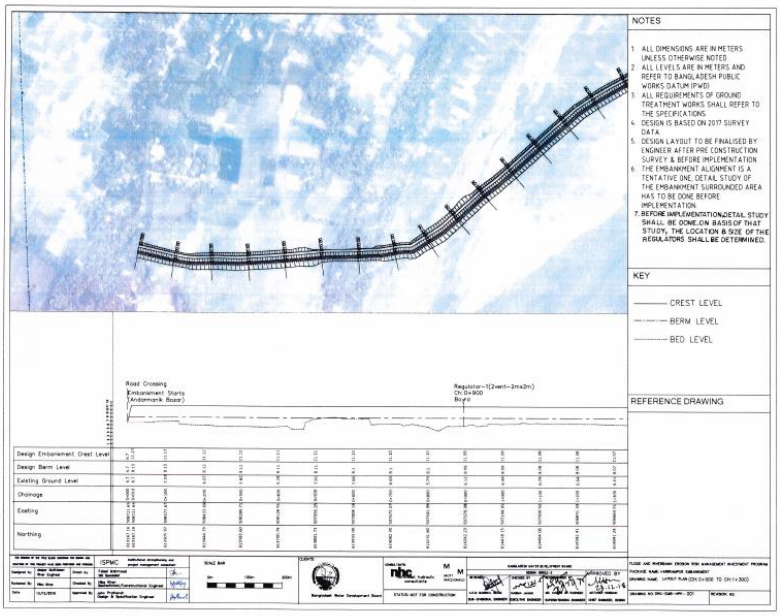


Figure 4-14: Longitudinal Profile of the Embankment in Harirampur (Source: BWDB)

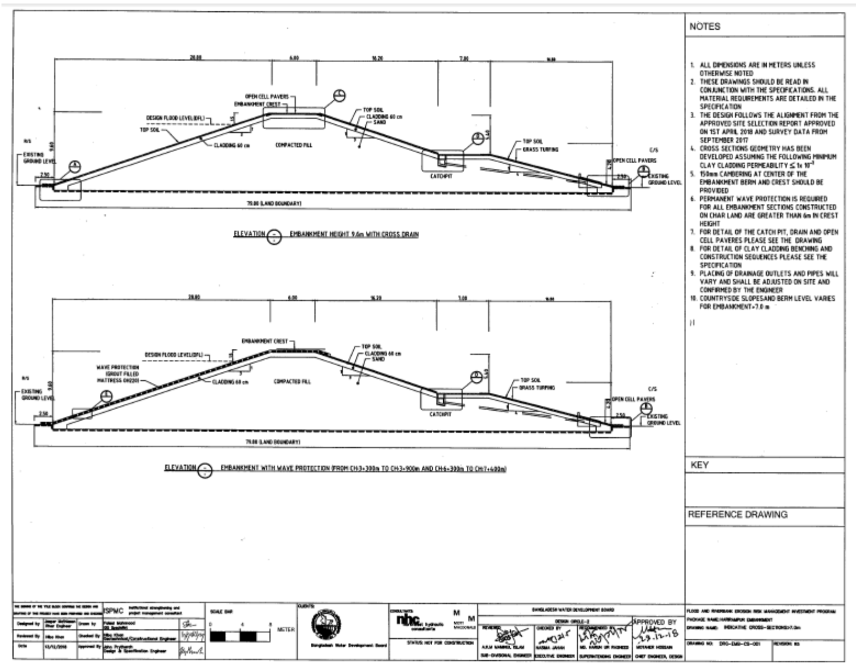


Figure 4-15: Typical Design section of the proposed Flood Control Embankment to be constructed along Left Bank of the Padma River in Harirampur (Source: BWDB).

4.4.10 Erosion Control Interventions (Implemented)

The situation during 2015 indicated that light protection is required in the upstream part (Figure 4-16). As the soil exhibits some clayey properties, no strong wave protection measures are required, only limited under water protection, such as mass dumped geo-bags can serve the purpose and also few geo-bag for wave protection. The Figure 4-16 depicts that, stretch length BC (7.8km) needs to be protected permanently to resist further erosion attack in this location. On the other hand, stretch length AB (2.2Km) is required with some light protection (geo-bag dumping) and stretch length CD (2km) requires no protection for the time being. But erosion both stretch lengths

AB and CD needs to be monitored regularly with upgraded protection in future during implementation Trance 2 of the project work.

Figure 4-16: Flood Embankment Protection with Sand Fill Geo-Bag in FREMIP at Harirumpur (source: Google)

The future river morphological change will be much influenced by the project. Without project, erosion will move downstream at high speed until it encounters more clayey area at Dhulsunra. This will result in a loss of an estimated 1.65 km^2 of newly developed char land (Figure 4-15). In the upstream, little erosion is expected and consequently little protective works are required. The project could provide a light protection in this place to reduce the due to low rates of erosion. With project the river channel will be stabilized the char moving downstream, but keeping a channel alongside the riverbank.

4.5 Field Visit for information collection and ground trothing

Field visit was conducted in the study area on August, 2020 when the riverine flooding situation and inundation were at the highest level in the Padma River and flood plain. Field visit was focused on the following objectives:

a) to physically observe the flood flow dynamics of the Padma River, the flood inundation and extents caused by both flood water and rainfall runoff ;
b) to interact with local stakeholder through conducting random discussion to know people's perception and ideas about union wise flood water inundation, extent and probable flood hazards;
c) to identify the existing status of the flood embankment and protective works by geo-bags and other; and
d) to validate the model results at field level and taking people's suggestions for mitigating the hazards and to collect primary information of the physical process of various resources, ecosystems and condition of the Padma river.

4.5.1 Field Visits Areas/Places for Collection of Information:

Areas visited were Routha Bazar in the boarder of Chala and Gopinathpur unions beside the Bhaatshala beel, Lesarganj Bazar of Lesraganj union and Andermanik Bazar in Boyra union. The local peoples suffered for long time due to flood inundation and hazards. So stakeholders and key informants were very much active and gave the information and share their experiences proactively in all discussions. In the visit, the flood embankment was found covered by herring bond brick soling road for facilitating the local communication. Flood level was very near the embankment crest level. The people informed that BWDB has implemented the protection works at the embankment slope with sand filled geo-bags to control river erosion but due to high flood level the protective works gone under water and could not been seen. Manikganj District Administration Office handed over a brief information report regarding river erosion, flood inundation, river and wetland conservation which was sent to National River Conservation Commission under Ministry of Shipping in the month of August 2020. It was reported that due to incessant rainfall, flood was occurred that affected the Dulsura union specially Dulshura bazar, Abidhara and Kamalapur. 28 families of these two villages lost their homestead land and two families lost the homestead land and their houses and all domestic resources by the river erosion. Twenty families were identified vulnerable to erosion risk. The char Mukundi Government Primary School and Dulsura union bazar were at high risk and under gone in the river due to massive river erosion of the Padma. Furthermore, it was also reported that BWDB took a dredging project to dredge about 38 km of Ichamati River to reduce the flood and river erosion. The local people gave their consent for the above mentioned dredging works and relevant information.

4.5.2 Field Survey and Field Level Consultation:

A comprehensive and structure questionnaire was prepared with respect of thesis objectives and outputs. The questions were open ended so that the stakeholders were felt comfortable to provide their information and answers to the questions freely. RRA was implemented at Loutha Bazar at Chala unions. The respondents were very cooperative and took interest in the RRA session. They were willingly participated in the session and provided information as per questioner relevant to the flood inundation and hazards caused by flood. The questionnaire was focused on union demarcations; river system, khals and beels; problems and anticipated flood depth, inundation area and hazards; seasonal agricultures crops grown and damages; fisheries production and damages caused by flood; communication hazards; sanitation and hygiene status and causes of flooding etc. Finally stakeholders confirmed their answer to the questions thrown to them. The author executed RRA was shown Figure 4-17.

Figure 4-17: Field level consultation during the field visit in Chala and Boyra unions of Harirampur

Chapter 5: Salient Features of the Model

5.1 Introduction

Now a days, several number of commercial and non-commercial software and modelling tools are accessible in the world for numerical modeling and analysis in GIS on the basis of purposes. Therefore, it is essential to understand the model concept in depth which is going to be applied and its sub-models, its limitations as well. The major tools used in this study are one and two dimensional numerical model HEC-RAS 5.0.7 beta version and Arc GIS for spatial data processing and HEC-GeoRAS for interfacing between HEC-RAS and Arc GIS. HEC-RAS and HEC-GeoRAS, an open source model which have excellent Graphical User Interfaces (GUI), were developed by US Army Corps of Engineers, USA. ArcGIS was developed in Environmental Systems Research Institute (ESRI) which enables to view, edit, create, and analyze geospatial data. Descriptions of these software tools are presented for dissemination of their function as below.

5.2 HEC-RAS

HEC-RAS is a computer based program that models the hydraulics of water flow through natural rivers and other channels. Prior to the recent update to Version 5.0.7, the program was one-dimensional meaning that there is no direct modeling of the hydraulic effect of cross section shape changes, bends, and other two and three-dimensional aspects of natural flow. The release of HEC-RAS version 5.0.7 introduced two-dimensional modeling of flow as well as sediment transfer modeling capabilities. The program was developed by the US Department of Defense, Army Corps of Engineers in order to manage the rivers, harbors, and other public works under their jurisdiction; it has found wide acceptance by many others institutes of different countries since its public release in 1995. HEC-RAS is designed to perform one and two-dimensional hydraulic flow calculations for a full network of natural system and constructed channels network. The following articles are the description of the major capabilities and application rationalities of HEC-RAS.

5.2.1 User Interface

The user interacts with HEC-RAS through a Graphical User Interface (GUI). The main focus in the design of the interface is to make it compatible with the software's as well as maintaining a high level of efficiency with ease for the user. The interface provides the following functions: i) file management; ii) data entry and editing; iii) hydraulic analyses; iv) tabulation and graphical displays of input and output data; v) inundation mapping and animations of water propagation; vi) reporting facilities and vii) context sensitive help.

5.2.2 Hydraulic Analysis Components

The HEC-RAS system is a versatile system which contains several river analysis components for: (i) steady flow water surface profile computations; (ii) one-and two-dimensional unsteady flow simulation; (iii) movable boundary sediment transport computations; and (iv) water quality analysis. A key element is, that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to these river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

5.2.3 Steady Flow Water Surface Profile Computations

This component of the modeling system is intended to calculate water surface profiles for steady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling sub-critical, super-critical, and mixed flow regimes water surface profiles. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation may be used in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e., hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions).

5.2.4 One and Two Dimensional Unsteady Flow Simulation

This component of the HEC-RAS modeling system is capable of simulating one dimensional; two dimensional; and combined one/two-dimensional unsteady flow through a full network of open channels, floodplains, and alluvial fans. The unsteady flow component can be used to performed subcritical, supercritical, and mixed flow regime (subcritical, supercritical, hydraulic jumps, and drawdowns) calculations in the unsteady flow computations module. An example of unsteady flow simulation has been shown in Appendix A-1.

The hydraulic calculations for cross-sections, bridges, culverts, and other hydraulic structures that were developed and used for the steady flow component were incorporated into the unsteady flow module. Special features of the unsteady flow component include: extensive hydraulic structure capabilities, Dam break analysis; levee/embankment breaching and overtopping; Pumping stations; Navigation Lock operations; Pressurized pipe systems; Automated calibration features; User defined rules; and combined one and two-dimensional unsteady flow modeling.

5.2.5 Movable Boundary Sediment Transport Computations

This component of the modeling system is intended for the simulation of one-dimensional sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods (typically years, although applications to single flood events are possible).The sediment transport potential is computed by grain size fraction, thereby allowing the simulation of hydraulic sorting and armoring. Major features include the ability to model a full network of streams, channel dredging, various levee and encroachment alternatives, and the use of several different equations for the computation of sediment transport.

The model is designed to simulate long-term trends of scour and deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and stage, or modifying the channel geometry. This system can be used to evaluate deposition in reservoirs, design channel contractions required to maintain navigation depths, predict the influence of dredging on the rate of deposition, estimate maximum possible scour during large flood events, and evaluate sedimentation volume and depth at different location in fixed channels.

5.2.6 Water Quality Analysis

This component of the integrated modeling system is intended to allow the user to perform riverine water quality analyses. An advection-dispersion module is included with this version of HEC–RAS, adding the capability to model water temperature. This new module uses the QUICKEST-

ULTIMATE explicit numerical scheme to solve the one-dimensional advection-dispersion equation using a control volume approach with a fully implemented heat energy budget. Transport and Fate of a limited set of water quality constituents is now also available in HEC-RAS. The currently available water quality constituents are: Dissolved Nitrogen (NO3-N, NO2-N, NH4-N, and Org-N); Dissolved Phosphorus (PO4- P and Org-P); Algae; Dissolved Oxygen (DO) and Carbonaceous Biological Oxygen Demand (CBOD).

5.2.7 Data Storage and Management

In this model, data storage is accomplished through the use of "flat" files (ASCII and binary), the HECDSS (Data Storage System), and HDF5 (Hierarchical Data Format, Version 5.0.7). User input data are stored in flat files under separate categories of project, plan, geometry, steady flow, unsteady flow, quasi-steady flow, sediment data, and water quality information.

Output data is predominantly stored in separate binary files (HEC and HDF5). Data can be transferred between HEC-RAS and other programs by utilizing the HEC-DSS. A view of data storage capability of HEC-RAS is shown in Appendix A-2.

Data management is accomplished through the user interface. The modeler is instructed as per request to enter a single filename for the project being developed. Once the project filename is entered, all other files are automatically created and named by the interface as needed. The interface provides for renaming, moving, and deletion of files on a project-by-project basis.

5.2.8 Graphics and Reporting

Graphics of this model include X-Y plots of the river system schematic, cross-sections, profiles, rating curves, hydrographs, and inundation mapping (Appendix A-3). A three-dimensional plot of multiple cross-sections is also provided. Flood Inundation mapping is accomplished in the HEC-RAS Mapper portion of the software. Inundation maps can also be animated and contain multiple background layers (terrain, aerial photography etc.). Tabular output is also available. Users can select from pre-defined tables or develop their own customized tables. All graphical and tabular output can be displayed on the screen, sent directly to a printer (or plotter), or passed through the Windows Clipboard to other software, such as a word-processor or spreadsheet. Reporting facilities allow for printed output of input data as well as output data. Reports can be customized as to the amount and type of information desired.

5.2.9 RAS Mapper

HEC-RAS has the capability to perform inundation mapping of water surface profile results directly from HEC-RAS (Appendix A-4). Using the HEC-RAS geometry and computed water surface profiles, inundation depth and floodplain boundary datasets are processed with the support of the RAS Mapper. Additional geospatial data can be generated for analysis of velocity, shear stress, stream power, ice thickness, and floodway encroachment data. In order to use the RAS Mapper for analysis, a terrain model is required in the binary raster floating-point format (**.flt**). The resultant depth grid is stored in the **.flt** format while the boundary dataset is stored in ESRI's Shape file format for use with geospatial software.

5.3 Theoretical Basis for ID/ 2D Hydrodynamic Calculation

5.3.1 1D Steady Flow Water Surface Elevation

HEC-RAS is currently capable of performing 1D water surface profile calculations for steady gradually varied flow in natural or constructed channels. Subcritical, supercritical and mixed flow regime water surface profiles can be calculated. Topics discussed in this section include: equations for basic profile calculations and applications of the momentum equation.

Equations for Basic Profile Calculations

Water surface profiles are computed from one cross section to the next by solving the energy equation with an iterative procedure, the standard step method. The Energy equation in between two sections is as follows:

$$Z_2 + Y_2 + \frac{a_2 V_2{}^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1{}^2}{2g} + h_e \quad (5\text{-}1)$$

Where,

Z_1, Z_2 = elevation of the main channel inverts in meter; Y_1, Y_2 = depth of water at cross sections in meter; V_1, V_2 = average velocities (total discharge/ total flow area) in meter/second; α_1, α_2 = velocity weighting coefficients; g = gravitational acceleration in meter^2/second and h_e = energy head loss in meter. A diagram showing the terms of the energy equation is shown in

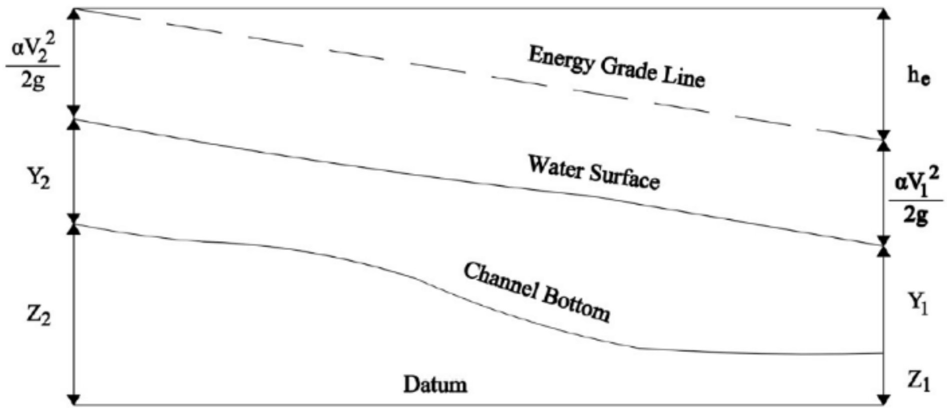


Figure 5-1: Representation of Terms in the Energy Equation

The energy head loss (he) is in m

$$h_e = L\bar{S}_f + C\left|\frac{a_2 V_2^2}{2g} - \frac{a_1 V_1^2}{2g}\right| \quad (5\text{-}2)$$

L = discharge weighted reach length in km; S_f = representative friction slope between two sections; C = expansion or contraction loss co-efficient. The distance weighted reach length, L in meter, is calculated as:

$$L = \frac{L_{lob}\bar{Q}_{lob}+L_{ch}\bar{Q}_{ch}+L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob}+\bar{Q}_{ch}+\bar{Q}_{rob}} \quad (5\text{-}3)$$

Where,

L_{lob}, L_{ch}, L_{rob}= x-section reach length in m specified for flow m^3/sec in the left overbank, main channel and right overbank respectively

Q_{lob} + Q_{ch} + Q_{rob} = arithmetic average of the flows in m^3/s between sections for the left Over bank, main channel and right overbank respectively

Q_{lob} , Q_{ch} , Q_{rob}= The flows/ discharges in m^3/s of left overbank, main channel and right overbank respectively

Application of Momentum Equation

Whenever the water surface passes through critical depth, the energy equation is not considered to be applicable. The energy equation is only applicable to the gradually varied flow situations. The transition from subcritical to supercritical or supercritical to subcritical is a rapidly varying flow situation. There are several instances when the transition from subcritical to supercritical and supercritical to subcritical flow can occur. These include significant changes in channel slope, bridge constrictions, drop structures and weirs, and stream junctions. In some of these instances, empirical equations can be used (such as at drop structures and weirs), while at others it is necessary to apply the momentum equation in order to obtain result. The momentum equation is derived from Newton's second law of motion:

$$\sum F_x = ma \quad (5\text{-}4)$$

Force = Mass x Acceleration (change in momentum)

(m and a are the mass and the acceleration respectively)

Applying Newton's second law of motion to a body of water enclosed by two cross sections at locations 1 and 2 (Figure 5-2), the following expression can be written for the change in momentum over a unit time:

$$\mathrm{P_2 - P_2 + W_x - F_f = Q\rho\Delta V_x} \quad (5\text{-}5)$$

Where,

P = Hydrologic pressure force at locations 1 and 2; W_x= Force due to the weight of water in the X direction.

F_x = Force due to external friction losses from 2 and 1; Q = Discharge in m^3/sec; P = Density of water and ΔV_x= Change on velocity from section 2 to section 1, in the X direction.

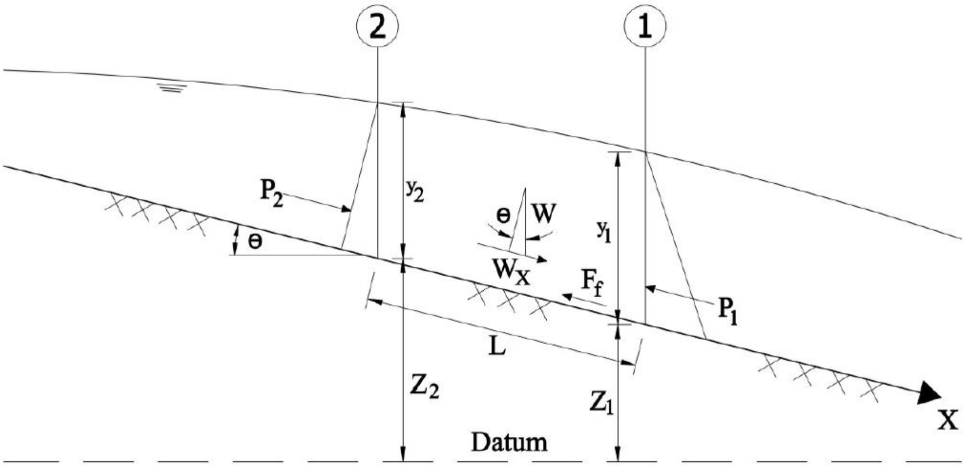


Figure 5-2: Application of Momentum Principle

$$P = \gamma A\bar{Y}cos\theta \quad (5\text{-}6)$$

The assumption of a hydrostatic pressure distribution is only valid for slopes less than 1:10. The cosθ for a slope of 1:10 (approximately 6 degrees) is equal proximately to 0.995. Because the slope of ordinary channels is far less than 1:10, the cosθ correction for depth can be set equal to 1.0 (Chow 1959). Therefore, the equations for the hydrostatic pressure force at sections 1 and 2 are as follows:

$$P_1 = \gamma A_1\bar{Y_1} \quad (5\text{-}7)$$

$$P_2 = \gamma A_2\bar{Y_2} \quad (5\text{-}8)$$

Where,

γ= unit weight of water; A_1= Wetted area of the cross section at locations 1 and 2; Yi= Depth measured from water surface to the centroid of the cross sectional area at locations 1 and 2.

The Weight of Water Force is: weight of water = (unit weight of water) x (volume of water)

$$W = \gamma\left(\frac{A_1 + A_2}{2}\right)L \quad (5\text{-}9)$$

$$W_x = W \times \sin\theta \quad (5\text{-}10)$$

$$\sin\theta = \frac{z_2 - z_1}{L} = S_0 \quad (5\text{-}11)$$

$$W_x = \gamma\left(\frac{A_1 + A_2}{2}\right)LS_0 \quad (5\text{-}12)$$

Where,

L= Distance between sections 1 and 2 along the X axis; S_f= Slope of the channel, based on mean bed elevations and Z_i= Mean bed elevation at locations 1 and 2.

Force to External Friction is:

$$F_f = \tau \bar{P} L \tag{5-13}$$

where,

τ = Shear Stress

$\bar{P}$: =Average wetted perimeter between section 1 and 2

$$\tau = \gamma \bar{R} \bar{S}_f \tag{5-14}$$

Where,

$\bar{R}$ = Average Hydraulic Radius (R=A/P)

$\bar{S}_f$= Slope of the energy grade line (friction slope)

$$F_f = \gamma \frac{\bar{A}}{\bar{P}} \bar{S}_f L \tag{5-15}$$

$$F_f = \gamma \left(\frac{A_1 + A_2}{2}\right) \bar{S}_f L \tag{5-16}$$

mass time acceleration is

$$ma = Q\rho \Delta V_x \tag{5-17}$$

$$\rho = \frac{\gamma}{g} \quad \text{and} \quad \Delta V_x = (\beta_1 V_1 - \beta_2 V_2)$$

$$ma = \frac{Q\gamma}{g}(\beta_1 V_1 - \beta_2 V_2) \tag{5-18}$$

Where,

β= momentum coefficient that accounts for a varying velocity distribution in irregular channels

Substituting back into equation 5-5 and assuming Q can vary from 2 to 1

$$\gamma A_2 \bar{Y}_2 - \gamma A_1 \bar{Y}_1 + \gamma \left(\frac{A_1 + A_2}{2}\right) L S_o - \gamma \left(\frac{A_1 + A_2}{2}\right) L \bar{S}_f = \frac{Q_1 \gamma}{g} \beta_1 V_1 - \frac{Q_2 \gamma}{g} \beta_2 V_2 \tag{5-19}$$

$$\frac{Q_2 \beta_2 V_2}{g} + A_2 \bar{Y}_2 + \left(\frac{A_1 + A_2}{2}\right) L S_o - \left(\frac{A_1 + A_2}{2}\right) L \bar{S}_f = \frac{Q_1 \beta_1 V_1}{g} + A_1 \bar{Y}_1 \tag{5-20}$$

$$\frac{Q_2{}^2 \beta_2}{g A_2} + A_2 \bar{Y}_2 + \left(\frac{A_1 + A_2}{2}\right) L S_o - \left(\frac{A_1 + A_2}{2}\right) L \bar{S}_f = \frac{Q_1{}^2 \beta_1}{g A_1} + A_1 \bar{Y}_1 \tag{5-21}$$

This is the functional form of the momentum equation that is used in HEC-RAS. All applications of the momentum equation within HEC-RAS are derived from this equation.

5.3.2 1D/2D Coupled Hydrodynamic Modeling

This study was focused on the development of 1D/2D coupled hydrodynamic modeling for the Padma River floodplain through HEC-RAS 5.0.7 published by USACE. The equations for 1D/2D coupled modeling have been stated in (Patel et al., 2017).

The HEC-RAS 5.0.7 is fully solved in using the 2D Saint-Venant equation (Brunner 2016b; Manual 2016; Quirogaa et al., 2016):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial x} = 0 \qquad (5\text{-}22)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -\frac{n^2 pg\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \xi}{\partial x} + pf + \frac{\partial}{\rho \partial x}(h\tau_{xx}) + \frac{\partial}{\rho \partial y}h\tau_{xy} \qquad (5\text{-}23)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -\frac{n^2 qg\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \xi}{\partial y} + qf + \frac{\partial}{\rho \partial y}(h\tau_{yy}) + \frac{\partial}{\rho \partial y}h\tau_{xy} \qquad (5\text{-}24)$$

where h is the water depth (meter), p and q are the specific flow in the x and y direction (m^2/sec), ζ is the surface elevation (meter), g is the acceleration due to gravity (m/sec^2), n is the Manning resistance, ρ is the water density (kg/m^3),, τ_{xy} and τ_{yy} are the components of the effective shear stress and f is the Coriolis (s^{-1}) (Quirogaa et al., 2016).

5.3.3 Advantage of 1D/2D Coupled Hydraulic Modeling

HEC-RAS can perform 1D modeling, 2D modeling (no 1D elements), and combined 1D and 2D modeling. The ability to perform combined 1D/2D modeling within the same unsteady flow model will allow users to work on larger river systems, utilizing 1D modeling where appropriate (for example : the main river system), and 2D modeling in areas that require a higher level of hydrodynamic fidelity.

5.4 Geographic Information System (GIS)

5.4.1 General

GISs are defined as computer systems capable of assembling, storing, manipulating, and displaying geographically referenced information (USGS, 1998). Originally developed as a tool for cartographers, GIS has recently gained widespread use in engineering design and analysis, especially in the fields of water quality, hydrology, and hydraulics. GIS provides a setting in which to overlay data layers and performs spatial queries, and thus create new spatial data.

The results can be digitally mapped and tabulated, facilitating efficient analysis and decision-making. Structurally, GIS consists of a computer environment that joins graphical elements (points, lines, polygons) with associated tabular attribute descriptions. This characteristic sets of GIS are apart from both computer-aided design software (geographic representation) and databases (tabular descriptive data). For example, in a GIS view of a river network, the graphical elements represent the location and shape of the rivers, whereas the attributes might describe the stream name, length, and flow rate. This one-to one relationship between each feature and its associated attributes makes the GIS environment unique. In order to provide a conceptual framework, it is necessary to first define some basic GIS constructions.

5.4.2 Data Models

Geographic elements in a GIS are typically described by one of three data models: vector, raster, or triangular irregular network. Each of these is described below.

Vector

Vector objects include three types of elements: points, lines, and polygons (Appendix A-5). A point is defined by a single set of Cartesian coordinates [easting (x), northing (y)]. A line is defined by a string of points in which the beginning and end points are called nodes, and intermediate points are called vertices (Smith, 1995). A straight line consists of two nodes and no vertices whereas a curved line consists of two nodes and a varying number of vertices. Three or more lines that connect to form an enclosed area define a polygon. Vector feature representation is typically used for linear feature modeling (roads, lakes, etc.), cartographic base maps and time-varying process modeling.

Raster

The raster data structure consists of a rectangular mesh of points joined with lines, creating a grid of uniformly sized square cells (Appendix A-6). Each cell is assigned a numerical value that defines the condition of any desired spatially varied quantity (Smith, 1995). Grids are the basis of analysis in raster GIS and are typically used for steady-state spatial modeling and two-dimensional surface representation. A land surface representation in the raster domain is called a digital elevation model (DEM).

Triangular Irregular Network (TIN)

A TIN is a triangulated mesh constructed on the (x, y) locations of a set of data points. To form the TIN, a perimeter around the data points is first established, called the convex hull. To connect the interior points, triangles are created with all internal angles as nearly equiangular as possible. This procedure is called Delaunay triangulation. By including the dimension of height (z) for each triangle vertex, the triangles can be raised and tilted to form a plane. The collection of all such triangular planes forms a representation of the land surface terrain in a considerable degree of detail (Appendix A-7). The TIN triangles are small where the land surface is complex and detailed such as river channels and larger in flat or gently sloping areas. Additional elevation data, such as spot elevations at summits and depressions and break lines, can also be included in the TIN model. Break lines represent significant terrain features like streams or roads. In three-dimensional surface representation and modeling, the TIN is generally the preferred as GIS data model. Some reasons for the TIN model preference include the following:

i. it requires a much smaller number of points than does a grid in order to represent the surface terrain with equal accuracy

ii. it can be readily adapted to variable complexity of terrain

iii. it supports point, line, and polygon features

iv. original input data is maintained in the model and honored in analysis

5.5 HEC-GeoRAS

5.5.1 General

HEC-GeoRAS is an ArcGIS extension specifically designed to process geo-spatial data for use with the Hydrologic Engineering Center River's Analysis System (HEC-RAS). The extension allows users to create an HEC-RAS import sample containing geometric attribute data form an existing Digital Terrain Model (DTM) and complementary data sets. Water surface profile results may also be managed to visualize inundation depths and boundaries. HEC-GeoRAS extension for ArcGIS is normally used as an interface method to provide a direct link to transfer information between the ArcGIS and the HEC-RAS5.0.7.

5.5.2 Overview of Requirements

HEC-GeoRAS 10.2 is an extension for use with ArcGIS 10.3 that provides the user with a set of procedures, tools, and utilities for the preparation of GIS data for import in to RAS and generation of GIS data from RAS output. While the GeoRAS tools are designed for users with limited geographic information systems (GIS) experience, extensive knowledge of ArcGIS is advantageous. However, users, however, must have experience in modeling with HEC-RAS5.0.7 along with a thorough understanding of river hydraulics to create and interpret GIS data sets properly.

5.5.3 Software Requirements

HEC-GeoRAS 10.2 is an extension use for ArcGIS 10.2. Both the 3D Analyst extension and the Spatial Analyst extension are required. The full functionality of HEC-GeoRAS 10.2 requires HEC-RAS 5.0.7 beta, or later, to import and export all of the GIS data options. Older versions of HEC-RAS 5.0.7 may be used, however, with limitations on importing roughness coefficients, ineffective flow data, blocked obstruct ions, levee data, hydraulic structures, and storage area data. Further, using the SDF to XML conversion tools provided, data exported from older versions of HEC-RAS should be converted to the latest XML file structure.

5.5.4 Data Requirements

HEC-GeoRAS requires a DTM in the form of a TIN or a GRID. The DTM must be a continuous surface which includes the bottom of the river channel and the floodplain to be modeled. Because all cross-sectional data will be extracted from the DTM, only high resolution DTMs representing the ground surface accurately should be considered for hydraulic modeling.

5.5.5 Getting Started

Start ArcMap. Load the HEC-GeoRAS tools by selecting Tools. Customize from the main ArcMap inter face and placing a check box next to HEC-GeoRAS. The Spatial Analyst and 3D Analyst extension will automatically load whenever required by the tools.

When the HEC-GeoRAS extension loads, menus and tools are automatically added to the ArcMap interface. Menus are denoted by text and tools appear as buttons. These menus and tools are intended exported HEC-RAS simulation results. The HEC-GeoRAS tool bar is to support the user in stepping through the geometric data development process and post processing of exported HEC-RAS simulation results. The HEC-GeoRAS tool bar is shown in Appendix A-8.

5.5.6 HEC-RAS Menus

The HEC-RAS menu options are RAS Geometry, RAS Mapping, ApUtilities, and Help. These menus are discussed below.

RAS Geometry

The RAS Geometry menu is used for pre-processing geometric data for the purpose of importing data into HEC-RAS interface. Items are listed in the RAS Geometry dropdown menu in the recommended (and sometimes required) order of completion. Items available from the RAS Geometry menu items are shown in Appendix A-9.

RAS Mapping

The RAS Mapping menu is used for post-processing exported HEC-RAS results. Items available from the RAS Mapping dropdown menu are listed in the required order of complete RAS Mapping menu are shown in Appendix A-10.

ApUtilites

Features available from the ApUtilities menu are used behind the scenes to manage the data layers created through GeoRAS. Also available from the ApUtilities menu is functionality to assign a unique HydroID to features. Only experienced users should use the items on the ApUtilities menu.

Help

The Help menu provides general online help information normally and the version is consistent with the ArcGIS product. It is being used with provide the version number.

5.6 HEC-Geo RAS Tools

There are several tools provided in the toolbar. A tool waits for user action after being activated and will either invoke a dialog or change the mouse pointer, indicating the need for further action. Appendix-11 shows the Summary of HEC-GeoRAS tools.

Chapter 6: Methodology, Data Collection and Model Setup

6.1 Introduction

Flood hazard map forms the foundation of risk management decision making process by providing information essential to understand the nature and characteristics of the community's vulnerability to flooding. The estimation of the flood depth and the extents of flooded area are essential in a flood-prone area for flood risk and hazard management. This chapter describes in a structured manner the methodology, data collection and model setup to achieve the study objectives as described in the chapter 1. Figure 6-1 shows the area of Harirampur considered for the study.

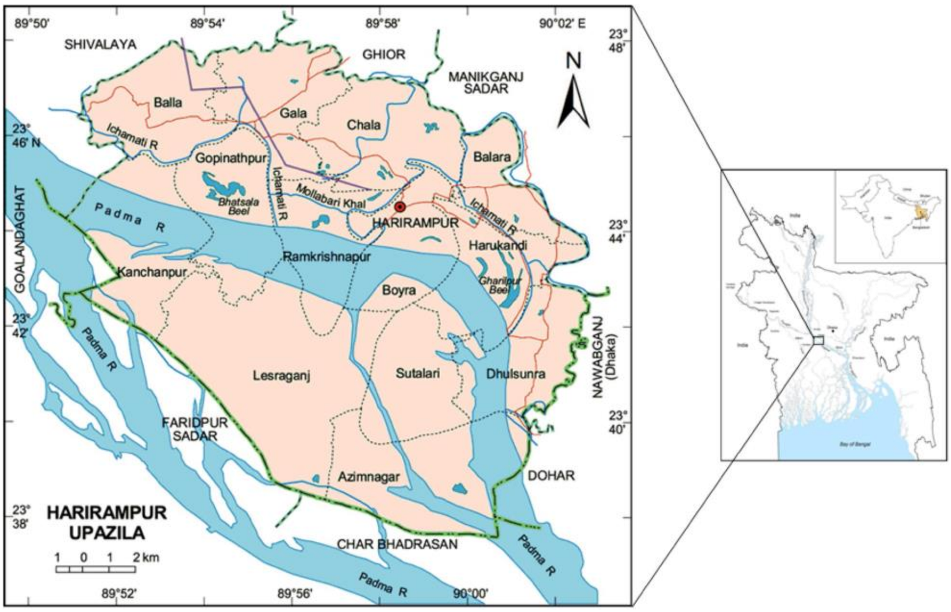


Figure 6-1: Study Area of Harirampur Upazilla (Source: Google)

6.2 Steps followed in Approach and Methodology

Modeling of any physical events needs clear understanding of the conceptual process by modeler for adapting iterative, interactive and integrated process for its development. Model refinements requires availability of quality and authenticate data as per scope of the study. A structured and systematic approach in three phases was followed in the current study showed in Figure 6-2. To achieve the study objectives, a brief description of the methodology and approaches in three phases are shown as below.

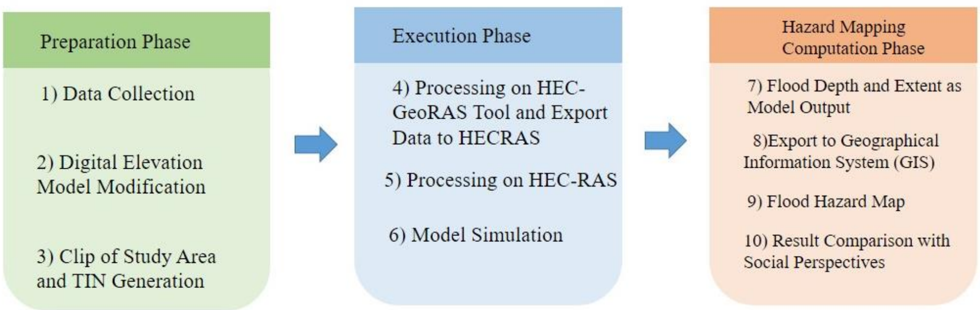


Figure 6-2: Phase wise Steps followed in Approach and Methodology

6.2.1 Preparation Phase

Data Collection

Various kinds of authentic data and information as per the requirement of the model collected to develop a good mathematical flood model. Both recent and previous year data were collected from BWDB and compiled as per model requirement. These data also form the basis for further analysis and interpretation of the model results leading to accurate assessment of hydrological condition of the Padma River and its floodplain. According to the modeling requirements, a significant amount of consistent data includes water level, discharge, cross-section, Digital Elevation Model (DEM) were collected and model setup has been made using these data. All collected data and information, sources and data location are summarized in the `table 6-1.

Table 6-1: Summary of Data Type, Data Sources, Data Locations and period of data collection

Data Type	Data Source	Data Locations	Periods (year)
Discharge and Water Level data	BWDB	Baruria Transit (SW91.9L)	1996-2018
Water level	BWDB	Bhagyakul (SW 93.4L)	1996-2018
Cross sections	BWDB	PADMA River (RMP1-RMP 8)	2008
DEM	Aster Dem	Bangladesh	2014

Discharge and Water level Data

The water level and discharge time series data of the Padma River at Baruria Transit station were collected from BWDB for the year 1996-2018. The hydrograph comprises data at an interval of one day. The discharge data of Baruria Transit station was used as the upstream boundary condition in the model.

The water level data of Bhagyakul for the year 1996-2018 was used as the downstream boundary condition in the model. The data of year 2010 was used to calibrate and while 2012 data was used to validate the hydro-dynamic model. Locations of two stations for which the historical discharge and water level data of the Padma River was collected from BWDB are shown in Figure 6-3 (a).

River Cross-section

River cross-sections of Padma River of the model reach were collected for the years of 2008 from Morphology Department of BWDB. BWDB collects cross- section data at 10 different designated stations in the Padma River. These cross-sections depict the shape and morphology of a river. Locations of the stations are shown in Figure 6-3 (b)

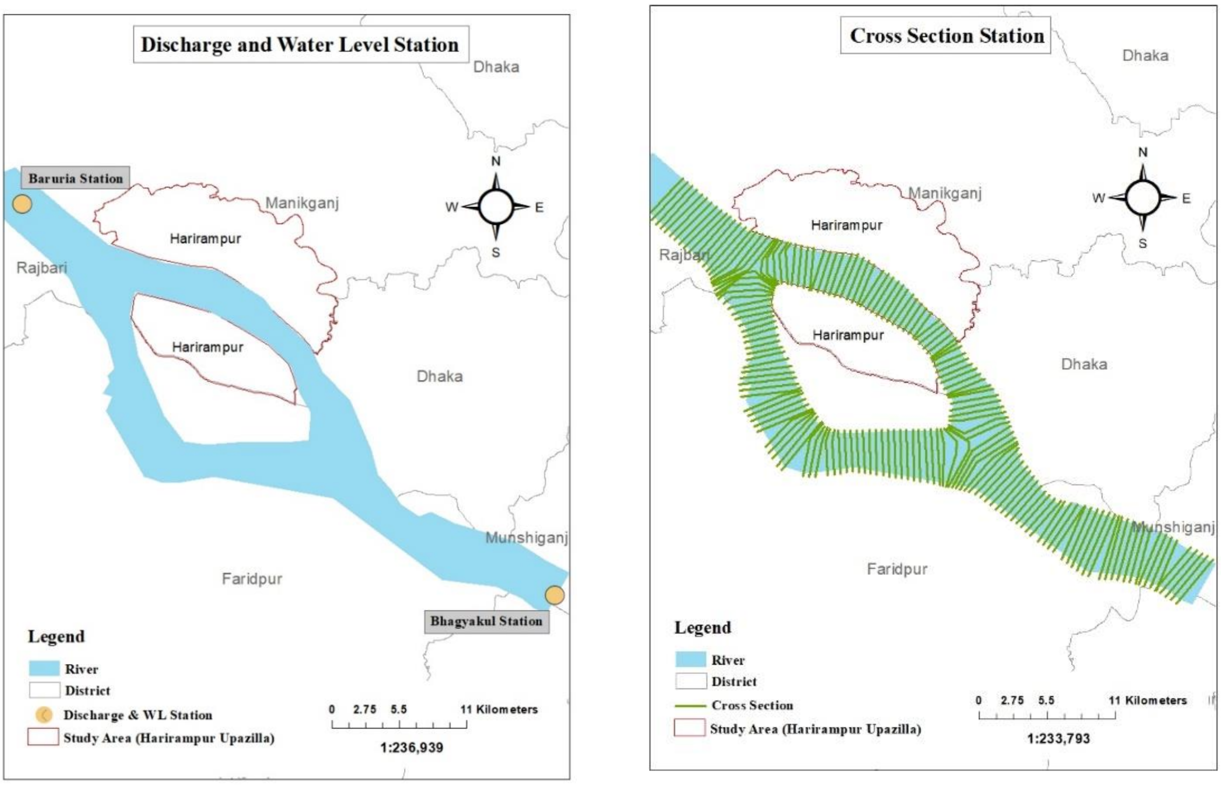
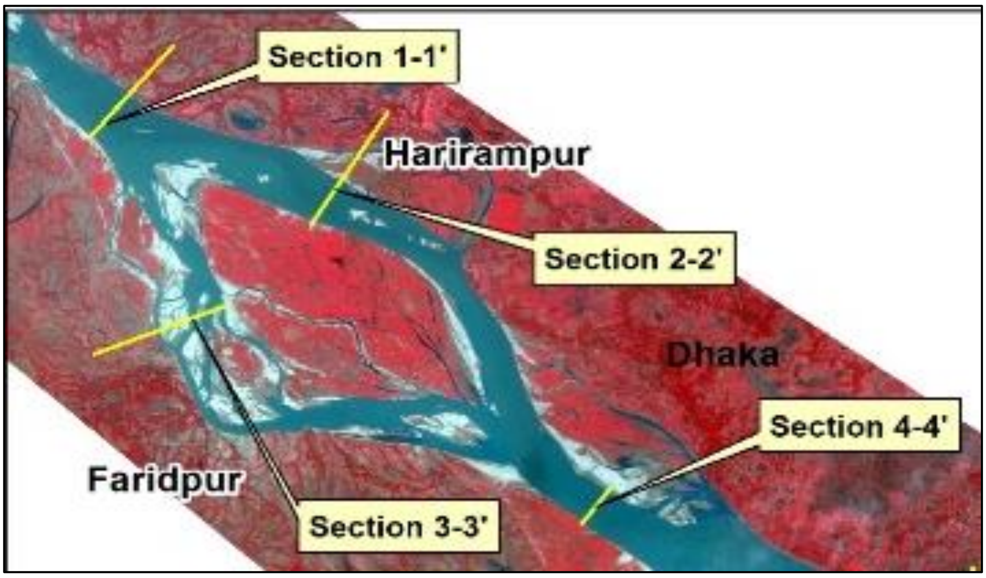


Figure 6-3: (a) Locations of Discharge and Water Level Station of Padma River, (b) Locations of cross-sections of Padma River used in the mode



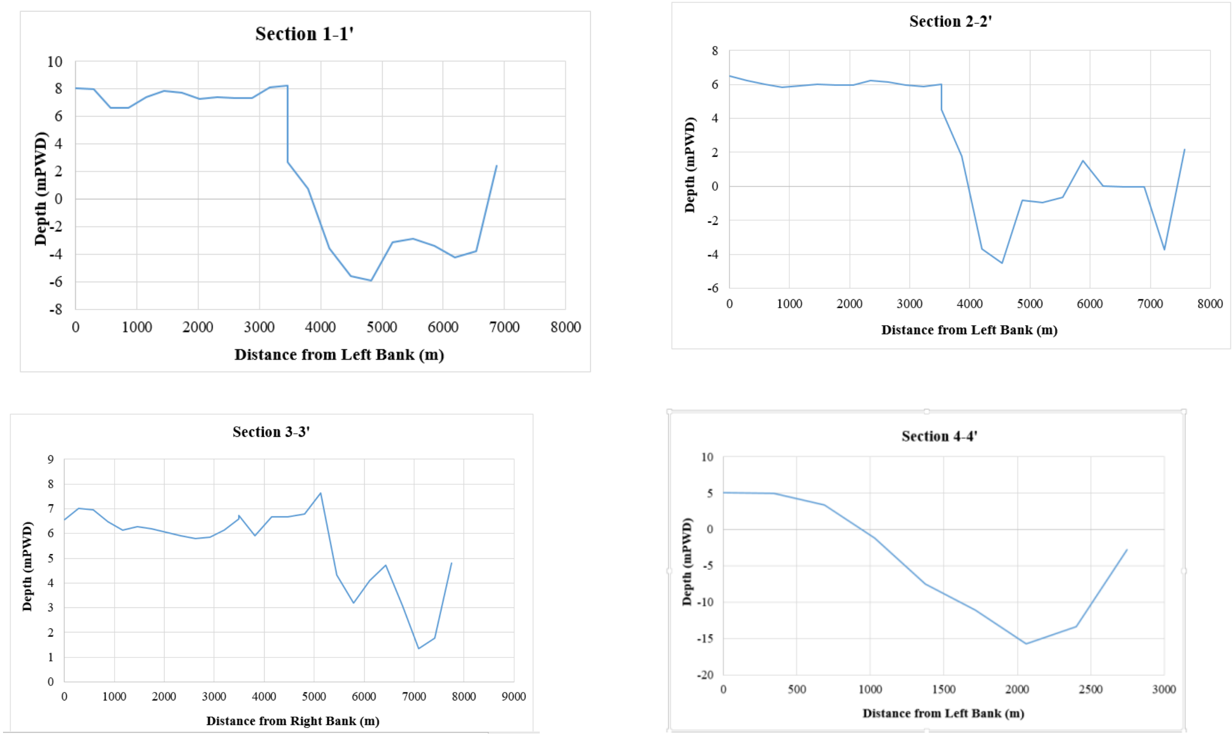


Figure 6-4: Location wise cross-section of the Padma River as per Image Map (Source: CEGIS)

Digital Elevation Model (DEM)

A digital elevation model (DEM) is a digital model or 3D representation of a terrain's surface level, created from terrain elevation data. DEM data identifies the elevations of the earth surface and to locate natural and relevant features on it (Rouf, 2015). A DEM can be represented as a raster (a grid of squares, also known as a height map when representing elevation) or as a vector-based triangular irregular network (TIN). The DEM could be acquired through techniques such as photogrammetry, lidar, land surveying, etc. DEMs are commonly built using data collected using remote sensing techniques, but it may also be built from land surveying. This data is required to take care flood plain and to formulate mathematical models for the study area. Each cell, and cell face, of the computational mesh of 2D flow area is pre-processed in order to develop detailed hydraulic property tables based on the underlying terrain used in the modeling process (Brunner et al., 2015).

The present study explores the hydrological modeling with the help of the ASTER digital elevation model (DEM). The Digital Elevation Model (DEM) of Bangladesh in raster format was collected from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), an imaging instrument onboard Terra, the flagship satellite of National Aeronautics and Space Administration (NASA)'s Earth Observing System (EOS). Figure 6-5 shows the DEM of Study Area.

Modification of Digital Elevation Model (DEM)

DEMs are increasingly used for visual and mathematical analysis of topography, landscapes and landforms, as well as modeling of surface processes. The accuracy of DEM is determined by data type and actual sampling technique of the surface during DEM creation. A DEM offers the most common way of showing topographic information and even enables the modeling of flow across topography, a controlling factor in distributed models of landform processes (Khan et al., 2017).

The Digital Elevation Model (DEM) of Bangladesh was collected from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), an imaging instrument onboard Terra, the flagship satellite of National Aeronautics and Space Administration (NASA)'s Earth Observing System (EOS). The DEM was in geographical coordinate system (GCS_WGS_1984). Geographic coordinate systems indicate location using longitude and latitude based on a sphere (or spheroid) while projected coordinate systems use X and Y based on a plane. Projections manage the distortion that is in evitable when a spherical earth is viewed as a flat map (Masood, 2011).

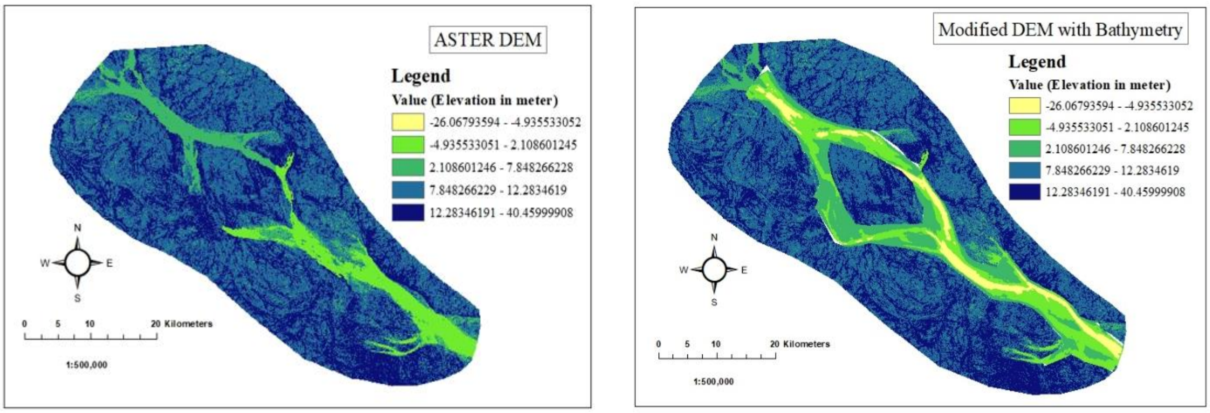


Figure 6-5: (a) Digital Elevation Model (DEM) of the Padma River reach and its surrounding model domain, (b) Digital Elevation Model (DEM) Modification.

All the data in the DEM were projected on to the geographical coordinate system (GCS_WGS_1984). The data comprises of a resolution of 30m x 30m grid. The elevation of the DEM were measured with respect to the mean sea level. All the elevations including topography of river cross sections, water surface elevation were measured from Public Work Datum (PWD). PWD is a horizontal datum believed originally to have zero at a determined Mean Sea Level (MSL) at Calcutta. PWD is located approximately 1.5 ft below the MSL established in India under the British Rule and brought to Bangladesh during the Great Trigonometric Survey. To adjust this difference in elevation, a slight modification of the collected DEM was made. The DEM after modification has been shown in Figure 6-5 (a) and 6-5(b)

Clipping of Study Area and Triangulated Irregular Network (TIN) Generation

After taking the modified DEM of Bangladesh, the shape file of Harirampur upazilla adjacent to the Padma River was superimposed. The DEM of this upazilla was clipped from the modified digital elevation model using the Clipping Tool in Arc Toolbox. And after that, study area was clipped from the DEM of Harirampur using the shape file of study area.

The purpose of the Raster to TIN tool is to create a Triangulated Irregular Network (TIN) whose surface does not deviate from the input raster by more than a specified Z tolerance. It is used to convert raster from a DEM to a TIN surface model. It is done by using the Raster to TIN tool in the Arc Toolbox.

6.2.2 Execution Phase

Pre-processing in HEC-GeoRAS

HEC-GeoRAS is an Arc GIS extension specifically designed to process geo spatial data to incorporate with the Hydrologic Engineering Center River's Analysis System (HEC- RAS). The extension allows users to create an HEC-RAS import file containing geometric attribute data form an existing Digital Terrain Model (DTM) and complementary data sets. Water surface profile results may also be processed to visualize inundation depths and boundaries. HEC-GeoRAS is organized as pre-processing (pre-RAS) and post- processing (post-RAS) facilitated by menu and buttons. In this study, only preprocessing was done in HEC-GeoRAS.

a. Pre-processing to Develop the RAS GIS Import File

The RAS GIS import file consists of geometric data necessary to perform hydraulic computations in HEC-RAS. Cross-sectional elevation data are derived from an existing Digital Terrain Model (DTM) of the channel and surrounding land surface, while cross-sectional properties are defined from points of intersection between RAS layers. The DTM may be in the form of a TIN or GRID. In this study, DTM was used as a TIN format.

The goal of this section is to develop the spatial data required to generate a HEC-RAS import file with a 3D river network and defined 3D cross sections. This extraction comprises several steps. These are development of a stream centerline, cross-sections cut lines, main channel banks, and flow path lines as shape files.

River Centerline Creation

The Padma River was represented by the stream centerline layer. The river was created by starting from the upstream end and working downstream following the deepest part of the channel. The river name was assigned as Padma and reach name were assigned as upper reach Padma, lower reach Padma.

Generally while creating a stream centerline layer some rules have been maintained. Following are the rules that have been maintained while creating stream centerline layer for Padma River. Figure 6-8 shows river centerline created for this study.

I. The stream centerline must have been in the downstream direction i.e. reach has been started at the upstream end and finished at the downstream end.
II. River reach must have a unique combination of its river name and reach name which has assigned in this study.

Riverbanks Creation

The riverbanks separate the main channel from the overbank areas when flooding occurs. It distinguishes, the resistance of the main channel and the overbanks. This is important for a steady-state simulation. Before beginning to create the banks theme, the following rules were important to remember to digitize:

I. There were exactly two bank lines per cross section. It was imperative to ensure to have a left and right bank defined, but no more than that.
II. Bank lines may be broken and it is not mandatory that the theme have to be a continuous poly line along a side of the channel.

III. Orientation of the banks lines was unimportant. Starting on the left or right of the stream centerline, as well as upstream or downstream was not matter. Creating this theme is optional when using GeoRAS. For this exercise, the banks theme was created so can be seen how accurate or inaccurate digitization ended up being. Figure 6-8 shows river banks created for this study.

Flow Path Creation

The Flow Path Centerlines theme was used to identify the hydraulic flow path in the left overbank, main channel, and right over bank. Creating the flow path centerline layer has assisted in properly laying out the cross-sectional cut lines. As the stream centerline already existed in this study, river centerline has been copied for the flow path in the main channel. Flow paths were created in the direction of flow (upstream to downstream). To complete assigning flow paths, the flow paths were digitized for the left and right overbanks. The following rules regarding flow path development were adhered:

I. All flow paths (left overbank, main channel, and right overbank) were drawn from upstream to downstream. A visual representation of the direction of the flow paths was used to maintain this rule using a line with arrow. The arrows should point towards downstream.

II. All three flow paths should be ensured at each cross section. The flow paths were used to derive downstream reach lengths in HEC-RAS. It is needed to be concerned with the buildings in the GRID. It should be noticed that the three flow paths for each reach, flowing from upstream to downstream. Once the digitization of the flow paths were completed, each flow path must now be identified as a left, right, or channel flow path. Obviously, the channel was the flow path along the center of the river channel. Determining the left and right flow path was accomplished by an upstream to downstream perspective. Geometric features (Flow paths) were created for this study are shown in Figure 6-6.

Cross-Sectional Cut Lines Creation

The location, position and expanse of cross sections are represented by the Cross Section Cut Line theme. This theme will identify the planar location of the cross sections and the station elevation data being extracted from the DTM along each cut line for use in HEC-RAS. The rules which were followed for developing this theme in this study are as follows:

I. Cross sectional cut lines must be pointed from the left overbank to the right overbank. Thus, each cut line from left to right was drawn, as it could look downstream.

II. As it could look at the Preprocess View, that would be from right to left. Cross sectional cut lines must cross each of the three flow paths and the two banks exactly once.

III. Cross sectional cut lines should be perpendicular to the direction of flow. (In some cases, this might be difficult to accomplish and still follow the other rules).
Cross sectional cut lines should not intersect.

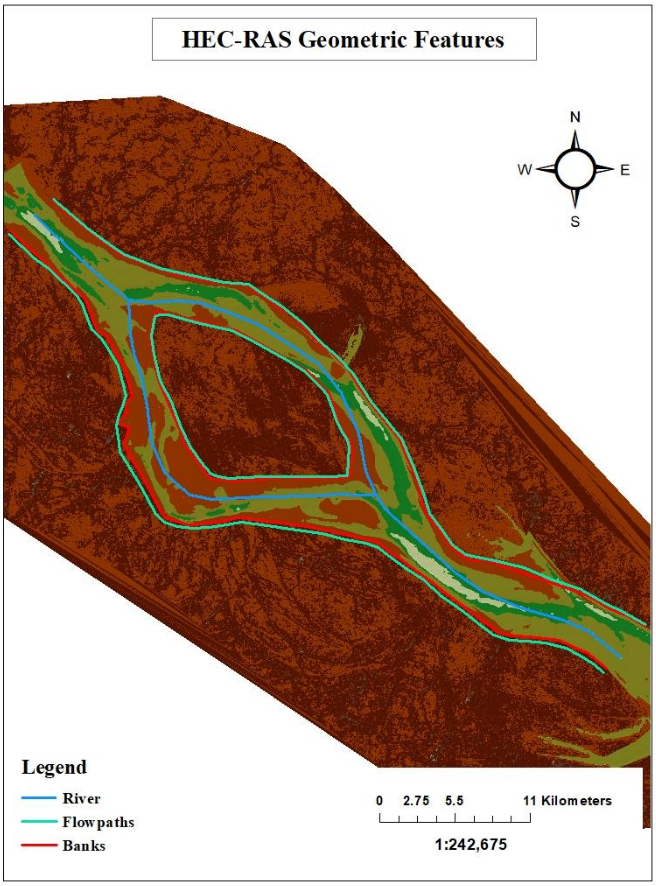


Figure 6-6: Geometric Features of the Padma River in HEC-RAS

To begin digitizing with the Cross Section Cut Line theme, it was specified as xscutlines.shp and began digitizing. Ten cross-section locations were chosen for the total study reach (48 km) and drawn according to the morphological station position (Figure 6-7). There are four key points to remember:

I. For buildings, it should be acted as if they do not exist in the TIN.
II. Locations should be eluded where possible bridges and/or overpasses exist in the TIN.
III. It should be ensured to place cross sections at upstream and downstream boundaries and
IV. Cut lines are to be started and ended well beyond the extent of the flow paths, since this theme will subsequently become the extent of the floodplains bounding polygon.

Generation of Additional Attributes and 3D Spatial Data

The polyline themes that have been created was used to extract the 3D attributes of the GRID through the theme's spatial relationship with the terrain. Extract spatial data were used to determine Manning's roughness value, 'n', for the HEC-RAS model. HEC- GeoRAS was used to process the intermediate data, the stream centerline (3D) and XS surface line (3D) in the subsequent steps of this study.

Centerline Completion

It was mandatory to check all the data were extracted or not for stream centerline. For this reason, completion of the centerline theme was done confirming all features from the RAS Geometry menu under “Stream Centerline Attributes”. The attribute table was then checked to ensure the properly extracted data.

Cross-Section Attributing

It was also important to ensure the all cross-section data were properly extracted. To complete the cross section layer, all features were ensured from the RAS Geometry toolbar under the “XS Cut Line Attributes’’. The 2D feature class of XS Cut Lines was intersected with the GRID to create a feature class with 3D cross section. After that, the attribute table and cross sections were examined in order to check their correctness.

6.2.3 Exporting GIS Data to HEC-RAS

The generation of the HEC-RAS import file was the last step of the HEC-GeoRAS preprocessing. The idea was to create a HEC-RAS input file in RAS Import format which includes the terrain elevation extracted from the TIN, the 3D stream centerline and the 3D cross sections themes as z values (z value is the elevation above public work datum and, for our case, is in units of meter). The “Extract GIS DATA” was clicked under the menu “RAS Geometry” from the HEC-GeoRAS toolbar. The default name GIS2RAS was accepted and saved in the selected folder.

Processing on HEC-RAS

Mathematical modeling is an advanced technology in engineering practice for predicting the flood water level. Hydrological and one-dimensional hydrodynamic models have been setup using HEC-package to forecast flood inundation map and hydrograph. Using this modeling software, a mathematical model for flood forecasting system has been developed. The various key steps during processing the model are described below.

1D Hydrodynamic Model

HEC-RAS 5.0.7 is an integrated software system, designed for interactive use in a multi- tasking environment and used to perform 1D water surface calculations. Four files are required to run a HEC-RAS 5.0.7 project. First, the `Project File' that acts as a file management tool and identifies which files are used in the model. The `Plan File' sets the model conditions as subcritical, supercritical, or mixed flow and runs the simulation. The `Geometry File' contains all the geometric attributes for the model. The `Steady Flow File' establishes the steady-state flow and boundary conditions at numerous points in time for the model. The `Unsteady Flow' File establishes the unsteady-state flow and boundary conditions at numerous points in time for the model. The 1D hydrodynamic model of the study areas was developed along with the mighty Padma River. The total length of river in the model was around 48 km.

Importing 1D Geometry Data

The geometric data editor was opened from the project window. The `import GIS data' from the `File' menu was opened. This operation needs to specify the unit system. The unit system was selected as SI units. The model comprises around 10 number of cross- sections of the river which were imported for the development of 1D hydrodynamic model (Figure 6-7). Initially for 1D calibration and validation, two boundary condition have been considered along the river upstream and downstream where boundary input data are collected from BWDB. The HEC-RAS 5.0.7 1D Model was calibrated for hydrological event of 2010 and validated for hydrological event of 2012.

Boundary Conditions:

Boundary condition is the conditions or physical process phenomenon occurring at the boundaries of the model. The Discharge data of 2010 and 2012 have been used as an upstream boundary condition for calibration and validation for unsteady flow simulations. Discharge data at Baruria Transit at upstream location and water level data at Bhagyakul at downstream location were used for both calibration and validation. Comparison of model simulation water level with observed water level data at (Baruria Transit) was made to finalize the roughness n value.

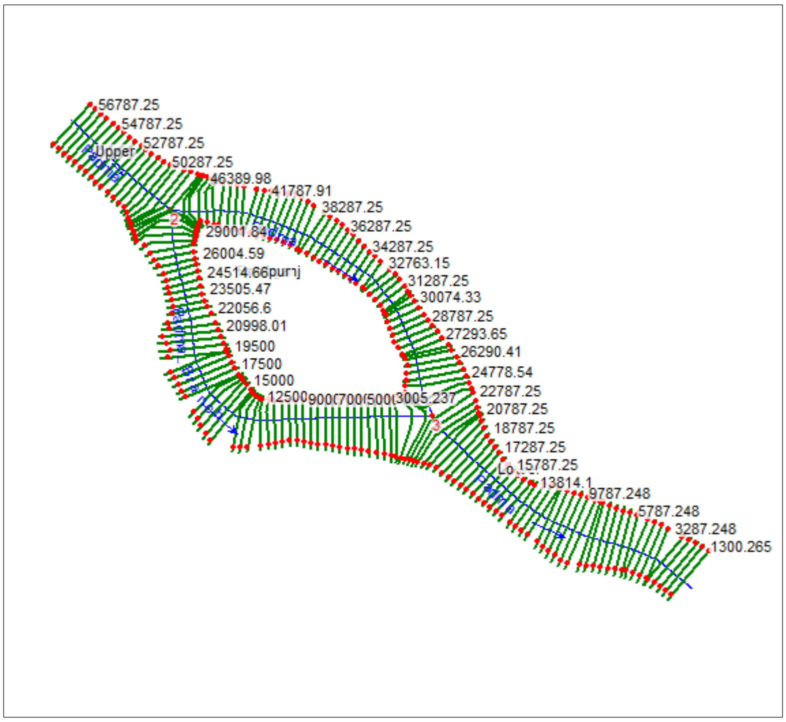


Figure 6-7: 1D geometric feature/cross sections of Padma River

Boundary Condition for Unsteady Analysis (1D):

The one-dimensional hydrodynamic model has one upstream boundary and one downstream boundary. Figure 6-8(a) shows the locations of the two boundary conditions. To calibrate the model, the boundary conditions were used from the observed discharge data at upstream location (Baruria Transit) and water level data at downstream location (Bhagyakul) for the year of 2010. To validate the model, the boundary conditions were used from the observed data for the year of 2012. Figure 6-8 (b) shows the location of model calibration and validation.

Model Calibration:

Before to simulate the model with base and different flow conditions, it is necessary to test the model's performance for optimum roughness value before model application. Sets of field data are pre-requisite for the testing. This testing provides an impression about the degree of the accuracy of the model in reproducing river physical processes. This process is known as calibration. Including consistent and rational set of theoretically defensible parameters and inputs of the model provide the basis for finalizing these inputs and parameter with good comparison of the model-generated outputs with the observed data. For this study, one-dimensional HEC-RAS 5.0.7 model was calibrated hydro-dynamically for the year 2010. Calibration was made using the water level data of Baruria Transit station in the river Padma.

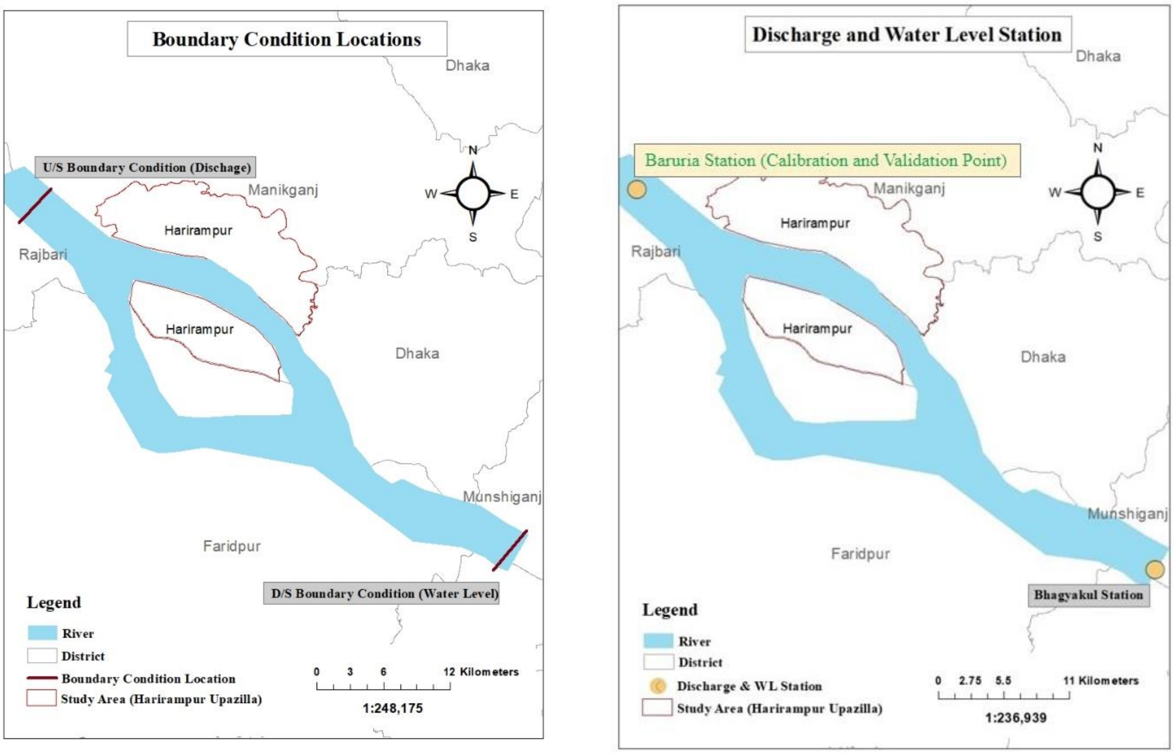


Figure 6-8: (a)Locations of Boundary Condition, (b) Location of Data used for Model Calibration and Validation

Model Validation

Model validation involves testing of a model with a data set representing 'observed' field data. This data set represents an independent source different from the data used to calibrate the model. Due to the uncertainty of prediction, this step is very important prior to widespread application of model output. The calibrated HEC-RAS based model was used to validate the time series data for the year 2012.

Model Performance Evaluation:

The quantitative statistics were divided into major categories: standard regression and error index. Standard regression statistics determine the strength of the linear relationship between simulated and measured data. Error indices quantify the deviation in the units of the data of interest (Legates and McCabe, 1999). For this study, two methods have been used: coefficient of determination R^2 as Standard regression statistics and Nash and Sutcliffe Simulation Efficiency (NSE) as dimensionless.

i. Coefficient of determination (R^2)

Coefficient of determination (R^2) describes the degree of collinearity between simulated and measured data (Rahman, 2015). R^2 ranges from 0 to 1, with higher values indicating less error variance and typically values greater than 0.5 are considered acceptable (Legates and McCabe, 1999). R^2 has been widely used for model evaluation, these statistics are oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999). Correlation Coefficient,

$$r = \frac{n\sum(xy-(\sum x)(\sum y))}{\sqrt{n(\sum x^2)-(\sum x)^2}\sqrt{n(\sum y^2)-(\sum y)^2}} \quad (6\text{-}1)$$

Where, x is the observation and y is the simulated value for the constituent being evaluated. Coefficient of determination, R^2 equals to r^2

ii. Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance (noise) compared to the measured data variance (information) (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in equation 6-2

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_m^t - Q_o^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q}_o\right)^2} \quad (6\text{-}2)$$

Where: Q_o is the mean of observed discharges, and $Q^t{}_m$ is modeled discharge. $Q_o{}^t$ is observed discharge at time t.

Nash–Sutcliffe efficiency can range from −∞ to 1. An efficiency of 1 (NSE = 1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (NSE = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (NSE < 0) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the numerator in the expression above), is larger than the data variance (described by the denominator). Essentially, the closer the model efficiency is to 1, the more accurate the model is. Threshold values to indicate a model of sufficient quality have been suggested between 0.5 < NSE < 0.65. For the case of regression procedures (i.e. when the total sum of squares can be partitioned into error and regression components), the Nash–Sutcliffe efficiency is equivalent to the coefficient of determination (R^2), thus ranging between 0 and 1.

The efficiency coefficient is sensitive to extreme values and might yield sub-optimal results when the dataset contains large outliers in it. To address this a modified version of NSE has been suggested where the sum of squares in the denominator of NSE is raised to 1 instead of 2 and the resulting modified NSE values compared to the original NSE values to assess the potential effect of extreme values. A test significance for NSE to assess its robustness has been proposed whereby the model can be objectively accepted or rejected based on the probability value of obtaining NSE > threshold (0.65 or other selected by the user).

Nash–Sutcliffe efficiency can be used to quantitatively describe the accuracy of model outputs other than discharge. This indicator can be used to describe the predictive accuracy of other models as long as there is observed data to compare the model results to. Nash–Sutcliffe Efficiency has been reported in scientific literature for model simulations of discharge; water quality constituents i.e. sediment, nitrogen, and phosphorus loading. Other applications are use of Nash–Sutcliffe coefficient to optimize parameter values of geophysical models, i.e. models to simulate the coupling between isotope behavior and soil evolution.

b. One Dimensional (1D) and Two Dimensional (2D) Coupled Hydrodynamic Model:

Layering Terrain Data:

HEC-RAS supports the use of digital terrain model for representing the bare earth ground surface. RAS DTM support is for raster data of many formats, but once processed, the data will be stored in the Geo Tiff format. A terrain layer is of primary importance for computing hydraulic properties (elevation-volume, elevation-wetted perimeter, elevation profiles, etc.), inundation depths and floodplain boundaries.

This can be done in RAS Mapper once the terrain model has been associated with a geometry and plan. This terrain can be used to visualize the floodplain geometry. So the grid-cell size must be small enough that it captures the features of the terrain. Prior to this, digital terrain model of study area has been created using new layer tool for preprocessing geometric data for 2D flow areas, computing flood depths and inundation boundaries from simulation results. While creating a terrain layer projection has been specified by selecting Bangladesh Transverse Mercator as an ESRI projection file (*.prj).Once a projection has been included, all the data will be projected into the selected coordinate system.

2D Flow Area Computational Mesh:

Two dimensional flow areas are regions of a model in which the flow through that region will be located at the beginning of a reach (as an upstream boundary to a reach), at the end of a reach (as a downstream boundary to a reach), or they can be located laterally to a reach. A polygon boundary for the 2D flow area along the Harirampur was drawn in the right side and left side of the Padma River. The HEC-RAS 2D modeling capability uses a Finite-Volume solution scheme. This algorithm was developed to allow for the use of a structured or unstructured computational mesh. A 200m x 200m grid resolution has been defined for the computational mesh (Figure 6-9).

Lateral Structures:

In case of lateral structures, HEC-RAS 5.0.7 has the ability to model lateral weir, gated spillways, culverts, diversion rating curves and an outlet time series. A single lateral weir, a weir and separate set of gates, a weir and group of culverts, or any combination of weir, gates, gates, culverts, rating curves and a time series outlet can be set up. In general a cross sections should be end at the inside top of the levee, and then the lateral structure option can be used to represent the top of the levee along the stream. On the upstream of the Padma River two lateral structures both side of the river were entered using lateral structure button from geometry data window. Figure 6-9 shows the introduction of lateral structure in model development.

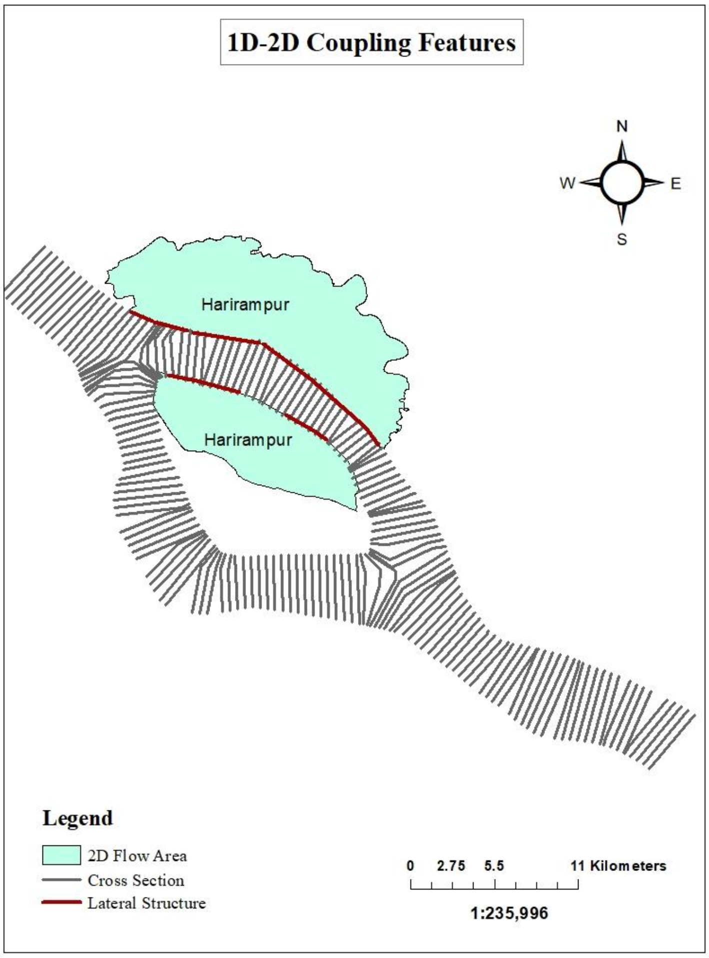


Figure 6-9: 2D Flow Area Computational Mesh and Lateral Structures in the 1D-2D Coupled Model

In this research, flood control embankment was considered as the lateral infrastructure. There is already existed flood control embankment from Kanchanpur to Ramkrisnapur about 7km length constructed earlier by BWDB and already damaged and eroded in different reaches with various scale.

The riverbank erosion affected areas are Ramkrishnapur union, Kanchanpur union, Gopinathpur union and Dhulshura union, with huge losses of standing crops, riverbank erosion of the Padma River made 100 families homeless in the Harirampur upazilla of Manikganj district in year 2019. In addition to that houses, roads and other infrastructures in the Manikganj district were devoured by the Padma River creating huge suffering of the flood-hit people.

The reason as reported by BWDB official was that in post-flood period, riverbank erosion took alarming turn devouring vast tract of farming land and houses and some business establishments. The BWDB took all necessary measures including dumping of sand filled geo bags and maintenances of embankments to check erosion along the banks of the Padma River.

Therefore, BWDB completed a FS study under the financial assistance of Asian Development Bank (ADB) and planned and designed the Flood Control Embankment from Ramkrishnapur to Dhulshura shown in image map (Fig 6-10) to be constructed to control flood and erosion.

Figure 6-10: Existing and Proposed Flood Control Embankment/Levee as Lateral Structure

The embankment has been designed with sufficiently strong having large base width and with provision of berm at country side. The average depth of embankment from the ground level is 6m and above. While the embankment crest level varies from 11 to 12m PWD. The ground level varies from 4 to 6 m PWD.

Defining Boundary Condition Location Line:

If a model needs a boundary condition then in HEC-RAS a boundary condition line can be drawn along the outer boundary of the area where you want the boundary condition to be located. Numbers of boundary conditions location has been defined and individual unique name has been given to each of the line. After all the boundary condition lines have been drawn along the flow areas, the geometry data has been saved. In unsteady flow data editor, boundary condition type's data for each boundary condition lines have been defined. In this study location of boundary condition line has been replaced until the model gives the correct inundation area.

Boundary Condition: Boundary condition is the conditions or phenomenon occurring at the U/S and D/S boundaries of the model. There are several different types of boundary conditions available for using. But in this study, only flow hydrographs and stage hydrographs were used as boundary conditions. The following is a short discussion of used boundary condition are:

Flow hydrograph:

A flow hydrograph can be used as either an upstream boundary or downstream boundary condition, but it is most commonly used as an upstream boundary condition.

Stage hydrograph:

A stage hydrograph can be used as either an upstream or downstream boundary condition. The user has the choice of either attaching a HEC-DSS file and pathname or entering the data directly into a table

Assuming Friction Slope as a Normal Depth Boundary Condition:

In case of using energy slope as a boundary condition, discrete energy slope at the downstream cross section is the correct assumption. But without computing, this is impossible to come by, and in order to compute, an energy slope has to be assumed. There are a few ways an energy slope for downstream boundary can be calculated and has been used in this study.

i. Measurement of the average bed slope of your stream in the profile plot.

ii. Measurement of the bed slope of the last two cross sections at the downstream boundary.

Water Surface Profile Generation:

The 1D and 2D coupled hydrodynamic model has been used to generate water surface profiles for unsteady flow conditions for the historical flood event 2007 and also flood flow for 100 year return period. The generated water surface profile data have been exported in GIS format data to develop flood inundation map and flood depth to produce flood hazard map.

Comparison and Hazard Mapping Phase

I. Mapping of Result and Visualization

Geospatial HEC-RAS results are managed in two distinct methods. (a) Dynamic map (b) Stored map

a. **Dynamic map** has been generated on-the-fly at the current view. This map is recomputed in RAS each time the map extents change based on the zoom level. It can also be animated within RAS Mapper. For each HEC-RAS Plan, specific output dynamics layers (water depth, velocity, and water surface elevation) have been automatically created for immediate visualization and analysis of the RAS simulation results.

b. **Stored map** data has been created and written to disk for permanent storage, exporting, sharing and analysis. Stored maps, however, are computed using the base resolution of the underlying Terrain Layer and stored to disk for permanent data storage. The datasets have been created and edited using the Manage Results Maps. Different types of map can be created and they are available based on the type of run performed. In this study, depth map type and inundation boundary map type have been created for exporting and analysis purpose. For serving the purpose of comparison and hazard mapping these maps have been used. Other than these, various maps can be produced in HEC-RAS 5.0.7. They are as follows

i. Water Surface Elevation; ii) Velocity; iii) Flow (1D); iv) Shear Stress; v) Stream power; vi) depth * Velocity; vii) Depth*Velocity^2; viii) Arrival Time; ix) Duration; x) Recession and xi) Percent time Inundation.

II. Development of flood hazard maps

Flood is a common yearly phenomenon. Every year, flood causes damage to the infra-structures, damaged to the standing agricultural and fisheries crops, water and sanitation, communication, socio-economic and homestead infrastructures, and wealth. When flood damages goes beyond the cooping capacity of the stakeholders it is called hazards. On the other hands, Flood brings many good things such as soil fertility, washed out all dirt and wastage. It also increases dilatation factor and create congenial environment for aquatic flora and fauna. Moreover, every year flood ensures the river functions and prevents its mortality. Flood has adverse impacts on environment and social livelihoods. Flood hazard maps under four different scenarios will show only the different hazards scale in each unions of Harirampur but no positive impacts of flood will be shown in the Flood Hazard Map.

Flood Hazard Assessment is the assessment of adverse effects of flooding in different sectors for a particular area. One or more parameters, such as flood duration, flood depth, flood wave velocity and rate of rise of water level can be used to assess flood hazard, which mainly depends on the area investigated and the characteristics of the flood (UN 1991). In this study, flood depth was considered in estimating flood hazard. A simple and modified procedure, similar to the technique used by (Dewan et al., 2007, Islam and Sado, 2000) was adopted in this study for flood hazard assessment. It is to be mentioned here that this process of estimating the flood hazard by Tasmia in her master's thesis on the Dharla River in Bangladesh Context was found successful. Accordingly attempt has also been made to use this concept for calculating Flood Hazard map of Harirampur in the Padma River for occurrence of riverine floods.

In order to assess flood hazard for each category of administrative unit, elevation data, a weighted score was estimated and hazard ranks were decided. This was accomplished by overlaying the GIS database on to the derived flood depth maps. The following steps were involved in assessing the flood as hazard.

a. Floodwater inundation extent and depth maps were overlaid with administrative unit, land use pattern to estimate the percent of area occupied by each category of flood water depth such as Flood Free (FF), F1, F2, F3 and F4. This land classification is almost similar to MPO land classification.

b. A weighted score for the acquired area percentage of each category of administrative unit, land use pattern was estimated using equation 6-3.

c Weighted score= Class 1*1.0+Class 2*3.0+Class 3*5.0+Class 4*7.0 (6-3)

After calculating the weighted score, points for each category of administrative unit, land use pattern was estimated on the basis of a linear interpolation between 0 and 10 (Very High Hazard). Hazard scale will be decreased with lower rank values)

d. On the basis of estimated points for each category of administrative unit, land use pattern, hazard ranks were determined. This was carried out by deciding four hazard ranks. The higher the ranking value, the more susceptible that particular class was considered to be more vulnerable to flood.

Chapter 7: Model Application and Results Analysis

7.1 Model Calibration Results

HEC-RAS model was setup for 48km long Padma River reach and calibrated using hydrograph (WL and Q) for twelve months with BWDB river cross-sectional data. The calibration was made using two different manning roughness (n) values (0.015 and 0.018 respectively) which is the most important parameter. Discharge hydrograph (Q) at Baruria Transit as upstream boundary condition (U/S) and water level (WL) hydrograph at Bhagyakul is another boundary conditions (D/S).

Calibration was made firstly for n value 0.018 and then secondly 0.015 and comparison was made between observed and simulated water level hydrographs. The comparison of observed and simulated hydrographs at station Baruria Transit shown in figure 7-1 and calibration results are shown in table 7.1

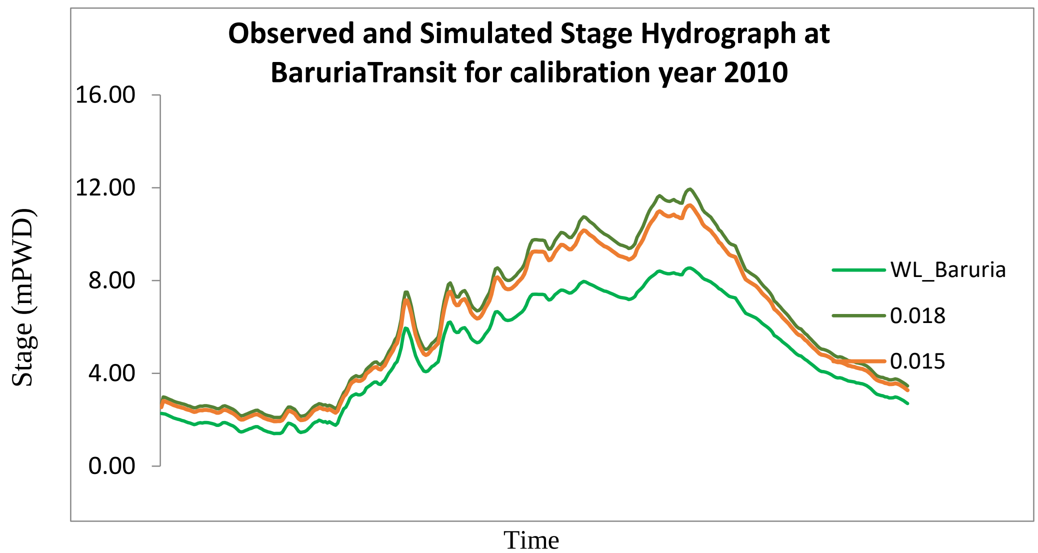


Figure 7-1: Observed and simulated stage hydrographs for calibration year 2010

Table 7-1: Summary matrix of various criteria of model runs under two manning roughness (n) for the year 2010 during calibration

n values	Visual Fitness	Volumetric fit	Coeff. Dett (R^2)	NSE	Remarks
0.018	Shape matches	More simulated volume than that of observed volume	0.9976	0.473	Not acceptable, NSE is < 0.5
0.015	Shape matches	Simulated volume more than observed but relatively less than that of observed volume for n value 0.018	0.9974	0.68	Acceptable as greater than 0.65

The best roughness value of n is 0.015 as it satisfied the statistical criteria and matching of shape of the hydrographs, volumetric fits, R^2 value 0.9974 which is nearly 1 and NSE value is 0.68 greater than 0.5 and near to maximum value of NSE and this n value accepted during calibration.

7.2 Model Validation Results

The model validation time series was different and independent than that of calibrated time series. Time series data for 2012 was taken for validation. Two visual criteria such as a) visual observation, b) volumetric fits and other two statistical criteria such as Co-efficient of Determination (R^2) and Nash-Sutcliffe Efficiency (NSE) as determined presented in Table 7-3. Due to uncertainty of prediction, this steps is very important prior to wide purposive application of model. The calibrated HEC-RAS model has been used to validate for the year 2012. The process of using different time series of equal length in both calibration and validation is called the **Split Sample Test**.

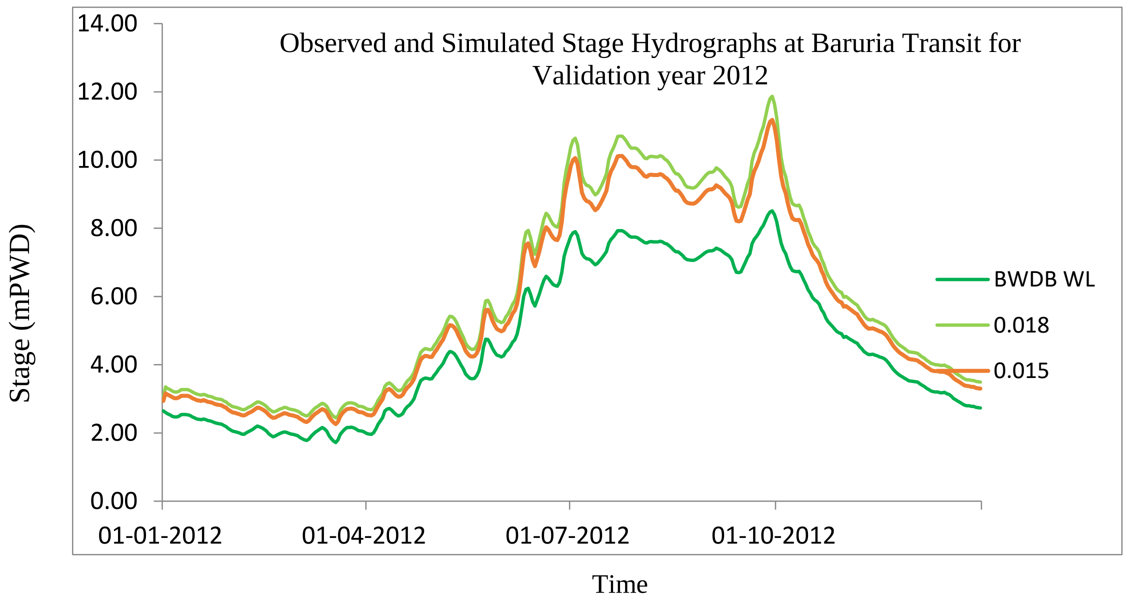


Figure 7-2: Observed and Simulated Stage Hydrographs in Validation for the year 2012

Table 7-2: The matrix of four criteria obtained during Validation of the Model Runs under Different Manning Roughness (n) for the year 2012.

n values	Visual Fitness	Volumetric Fit	Coeff. Dett (R^2)	NSE	Remarks
0.018	Shape matches	More simulated volume than observed volume	0.997	0.488 which is less than 0.5	Not accepted
0.015	Shape matches	Simulated volume is relatively more than that of observed but less than for n value 0.018	0.998	0.690 which is very near to the max value of NSE	Accepted

The best roughness value of n 0.015 also satisfied all four selected criteria a) matching of shape of hydrographs (Figure 7-2), b) annual volume fits c) R^2 value is 0.998 which is nearly 1 and d) NSE value is 0.69 very near to the maximum value as set for NSE as and greater than 0.5 accepted during validation as well. However, the optimum roughness value of n for flood plain has been fixed 0.030 from literature review and expert judgments. Now the model is ready to apply for prediction of anticipated results four different scenarios such as without embankment, with embankment, breaching of embankment and overtopping of embankment respectively.

7.3 Model Application

The integrated model was calibrated and validated properly for the year 2010 and 2012 respectively. The boundary conditions in the upstream at Baruria Transit was discharge time series while the downstream boundary conditions was water level time series observed at Bhagyakul (93.4L) of BWDB. The simulated model water level time series was compared with observed water level data of BWDB Baruria Transit station. The river bathymetry data used in the model was taken from BWDB while ASTER DEM data was taken from Survey of Bangladesh (SoB) for describing the associated flood plain. The optimum value of roughness n value determined from calibration and verification process. The model made ready for application. The model applied for peak flood flow of 3rd August, 2007 and flood flow of 100 year return period as determined from frequency analysis.

7.4 Interventions or Lateral Infrastructures for model application

The interventions (embankment) was considered to control the flood propagation to the flood plain and for erosion mitigation with river training works are practiced by BWDB under the FREMIP (Flood and River Erosion Mitigation Project) financed by Asian Development Bank (ADB). This flood control embankment with erosion protection has specific hydraulic design considering the climate change. The typical design section and length of flood control embankment is given in details in chapter 4(four) and erosion control interventions normally with Geo-bag dumping and pitching are being made under this project.

7.5 Rationale for Flood Inundation Map Preparation

Following selected dates of the respective years shown in the table 7-3 were taken for preparation of the flood inundation maps from the model outputs. The dates were taken from the results of image analysis as determined by North West Hydraulic Consultant (NHC) and presented in ADB reports, 2013. These dates had been taken due to highest flood inundation extents, highest water level and maximum precipitation observed in the Padma River Left Bank (PLB-1) area.

Table 7-3: Highest water level, precipitation and inundation

Date of imagery	WL at Aricha (m)	Precipitation (mm)	Inundation (% of gross area) at PLB-
26-Aug-98	10.19	2011	60.6
10-Sep-98	10.75	2219	62.1
17-Sep-98	9.28	2219	48.5
23-Jul-04	10.26	813	45.3
3-Aug-07	10.67	916	45.6

(Source: NHC reports, 2013)

7.6 Scenarios of Model Applications

The calibrated and validated model was then applied for the flood occurred on 3rd August 2007 chosen through frequency analysis and highest flood level. In 1998 the maximum flow was found nearly the flow determined by frequency analysis for 100 year return period.

The rationale for selection of flood year 2007 for application over 1998 flood was that the flood which prolonged waterlogged of whole Bangladesh except Dinajpur remained more than 3 (three) months and caused severe damage in the affected area and made the area more vulnerable to flood hazard than that of previous year flood. Using Log Pearson type-III method, the discharge for 100 year return period is 1, 51,583 m^3/s whereas the 1998 flood year maximum discharge is 1, 41,935 m^3/s, and 2007 year flood maximum discharge is146, 865 m^3/s which was more than that of 50 year return period flow of 143,000 m^3/s. Considering above information, model was applied for peak flow of 03 August, 2007 and flow of 100 years return period.

In the study, two scenarios i.e. i) inundation due to embankment breaching and ii) inundation due to overtopping of flood control embankment were considered for model application as per scope of the study, but to understand the total physical process of flood inundation due embankment breaching and overtopping and its response to hazards, two more scenarios were developed such as i) the flood inundation without any interventions and ii) flood inundation with implementation of 17 km full flood control embankment in the left bank of the Padma river. Accordingly calibrated and validated model was applied considering design information, breaching information for all four scenarios to assess the flood inundation extent and depth in different unions of Harirampur and scenarios are summarized in Table 7-4.

Table 7-4: Summary of the interventions for four different scenarios

Sl no	Scenario name	Description of scenarios
1	No Flood Control (FC) Embankment (Scenario 1)	Normal river hydro-morphological process prevails and without any hydraulic water control infrastructures to control flood flow. Model generates the flood inundation (depth and extent) maps of both parts of Harirampur, falls left side of the Padma River and within the conveyance and charland of the river.
2	Full FC Embankment (Scenario 2)	A proposed full flood control embankment of 17 km length from Kanchanpur union to Dhulshura union on the left bank of the River Padma. The proposed embankment designed with sufficiently strong having large base width and with provision of berm at country side. The average depth of embankment from ground level to crest level is about 6m and above. The embankment crest level varies from 11 to 12m PWD and ground level varies from 4 to 6 m PWD were considered in the model.
3	Embankment Overtopping (Scenario 3)	Assuming flood water entered in the mainland part located in the left side of the Padma river by overtopping of embankment due to rise of water level which crossed danger level. Furthermore, the crest level of embankment may be lowered due to inadequate compaction which results lowering of

Sl no	Scenario name	Description of scenarios
		embankment crest level. In this case, 10 union unions may not be inundated except the unions which are exposed and nearer to the flood control embankment on the basis of existing terrain level.
4	Embankment Breaching (Scenario 4)	Flood water entered through breaching of flood control embankment about 3.5 km length at two locations i.e. 2.5 km at Andharmanik in Boyra union and 1Km at Gopinathpur union (sources: the daily newspaper 'The new age published on May 19, 2019).

7.7 Model Application for Flood Year 2007

7.7.1 Flood Inundation Mapping and Analysis of Flood Extent and Depths.

Floodplain delineation was done by HEC-RAS 5.0.7 software itself and shown in RAS Mapper. Shape file of different flood extent produced for different time. Then the shape file has been exported into GIS and calculated the area of inundation including the main channel. Applied model yielded inundation area and percentage under four different scenarios as described earlier. The table 7-5 inundation extent (km^2) at different flood depth (m) **considering river as an integrated part** of Harirampur while table 7-6 shows percentage of inundation areas considering river areas to total areas respectively. Discussion of the results for each scenarios are given in the following sections.

Table 7-5 Inundation depth (m) and extent (km^2) under four different scenarios of flood on 03 August 2007 inclusive of river area

			Area Inundated (km^2) inclusive of river area					
	Scenario name	FF (Flood Free)	F1 (0.0-0.9m)	F2 (0.9-1.8m)	F3 (1.8-3.6m)	F4 (>3.6m)	Inundated area (F1-F4)	Total area
Model Scenarios	Scenario 01 (Without Embankment)	99.51	25.60	26.94	30.96	60.04	143.55	243.06
	Scenario 02 (Proposed Embankment)	132.89	15.78	19.44	16.30	58.64	110.17	243.06
	Scenario 03 (Overtop of Embankment)	105.61	25.27	25.19	24.12	62.88	137.45	243.06
	Scenario 04 (Breach of Embankment)	113.21	22.91	23.12	21.17	62.65	129.85	243.06

Table 7-6 Percentage of Inundation extent to total area of Harirampur in four different scenarios of flood on 03 August 2007 inclusive of river area.

	Name of Scenarios	**FF (% area)**	**F1 (% area)**	**F2 (% area)**	**F3 (% area)**	**F4 (% area)**	**% of Inundation**
Model Scenarios	Scenario 01 (Without Embankment)	40.94	10.53	11.08	12.74	24.70	59.06
	Scenario 02 (Proposed Embankment)	54.67	6.49	8.00	6.71	24.13	45.33
	Scenario 03 (Overtopping of Embankment)	43.45	10.39	10.36	9.92	25.87	56.55
	Scenario 04 (Breach of Embankment)	46.58	9.42	9.51	8.71	25.78	53.42

Scenario 1: without any flood control embankment inclusive of river area

In this scenario, model generated flood extent and inundation depth of Harirampur which consists of thirteen unions including river areas. Significant part of land of Balara, Harukandi, Dhulshura and Sutalari, Azimnagar, Lesarganj (partly) were flood free (FF). And remaining lands in other unions including the above mentioned unions were flooded in mixed distribution such as 10.53% land in F1 and 11.08% land in F2. While 12.74 % land in F3, 24.70 % land in F4. Three unions of Harirampur falls mostly within the river conveyance are F4 lands. Almost 41% land area which is flood free and the total flood inundation area is almost 59%. Flood Inundation extent and flood depth map considering river area shown in Figure 7-3

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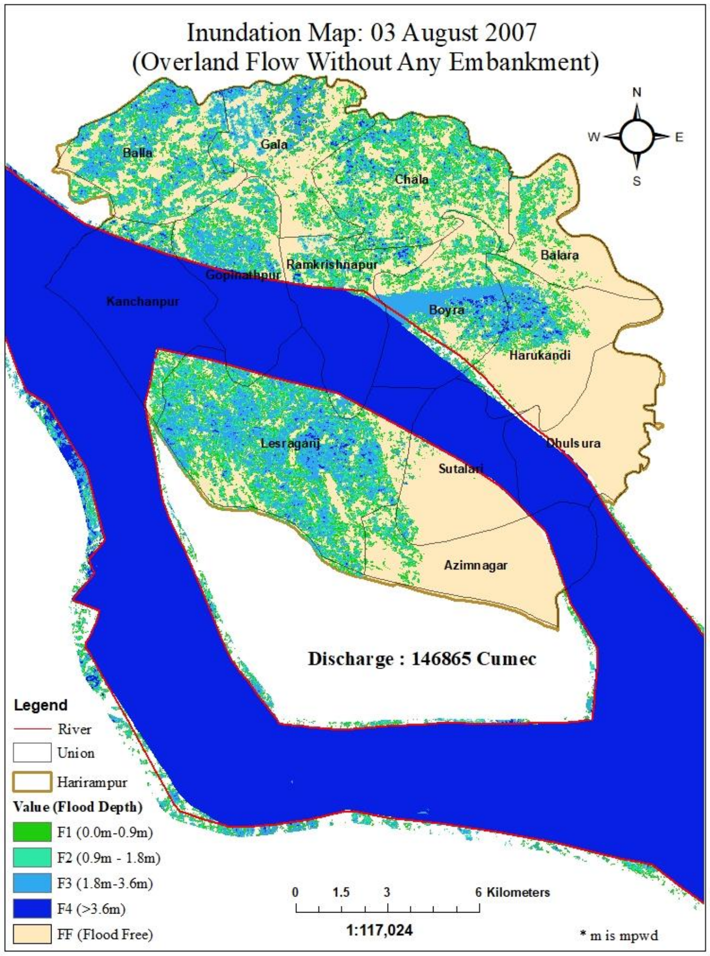

Figure 7-3: Flood Inundation map for 03 August 2007 without any flood control embankment

Scenario 2: Assuming there exists full flood control embankment inclusive of river area

This scenario considered full protection given by 17 km of flood control embankment in the left bank of the Padma River. Model generated flood extent and inundation map of Harirampur upazilla. Significant part of land of Balla, Gala, Chela, Boyra, Balara, Harukandi, Dhulshura and Sutalari, Azimnagar, Lesarganj (partly) remained as flood free (FF). And remaining lands in other unions as well the above mentioned unions were in mixed distribution such as 6.49% land in F1 and 8.00% land in F2. While 6.71% land in F3, 24.13% land in F4. In all the scenarios, the percentage of land in F4 was maximum in every scenarios. It is worthwhile to mention here that inundation extent in different depth during wet seasons were due to overland flow gradually moving to the river and accumulated in different parts of the ten unions in left bank of the Harirampur. Almost 55% land area which is maximum of all scenarios is flood free and the total flood inundation area is almost 45%. Flood Inundation extent and flood depth map shown in Figure 7-4.

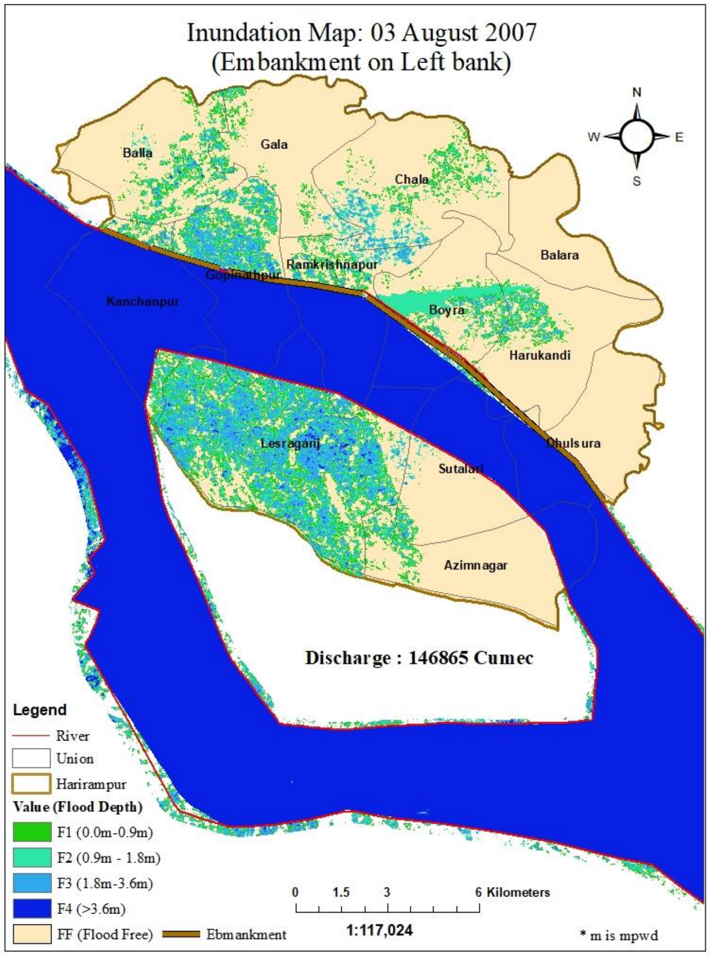

Figure 7-4: Flood Inundation map for proposed full flood control embankment in the left side of the Padma River on 03 August 2007.

Scenario 3: Overtopping of full flood control embankment inclusive of river area

In this scenario, it was assumed that flood flow level 11.47m would overtop the embankment crest m uniformly of 17km embankment and flood water would entered in the left bank side unions of Harirampur. The model generated flood extent and inundation map of Harirampur upazilla. Significant part of land of Harukandi, Sutalari, Dhulshura, Azimnagar, Lesarganj was flood free (FF). And remaining lands in other unions including the above mentioned unions were in mixed distribution in different flood depth such as 10.39% land in F1 and 10.36% land in F2. While 9.92% land in F3, 25.87% land in F4. Almost 43.45% land area is flood free and the total flood inundation area is 56.55%. Flood Inundation extent and flood depth map shown in figure 7-5.

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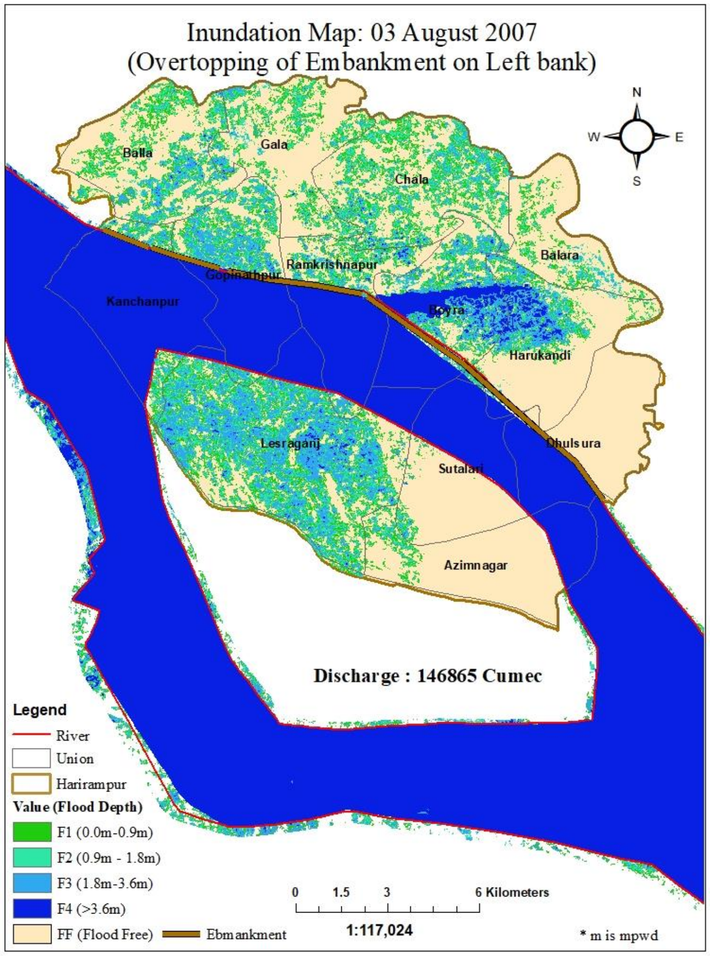

Figure 7-5: Flood Inundation map for 03 August 2007 with overtopping of embankment on the Left Bank the Padma River

Scenario 4: Embankment Breaching (3.5 km length) in two locations inclusive of river area

In this scenario, it was considered that breaching of flood embankment as per field conditions occurred at two locations (one location was at Gopinathpur of 1km breach while the other was at Andermanik, Boyra of 2.5 km in length) and total length of breaching was in total 3.5 km. The model generated flood extent and inundation map of Harirampur for all the thirteen unions. Significant part of land of Balla, Gala, Harukandi, Dhulshura, Sutalari and Azimnagar, were flood free (FF). And remaining lands in other unions including the above mentioned unions were in mixed distribution such as 9.42% land in F1 and 9.51% land in F2. While 8.71% land in F3, 25.78% land in F4. It was to be mentioned here that three unions of Harirampur falls fully within the river conveyance in F4.

Almost 46.58 % land area is flood free and the total flood inundation area is 53.42%. Flood Inundation extent and flood depth map shown in Figure 7-6.

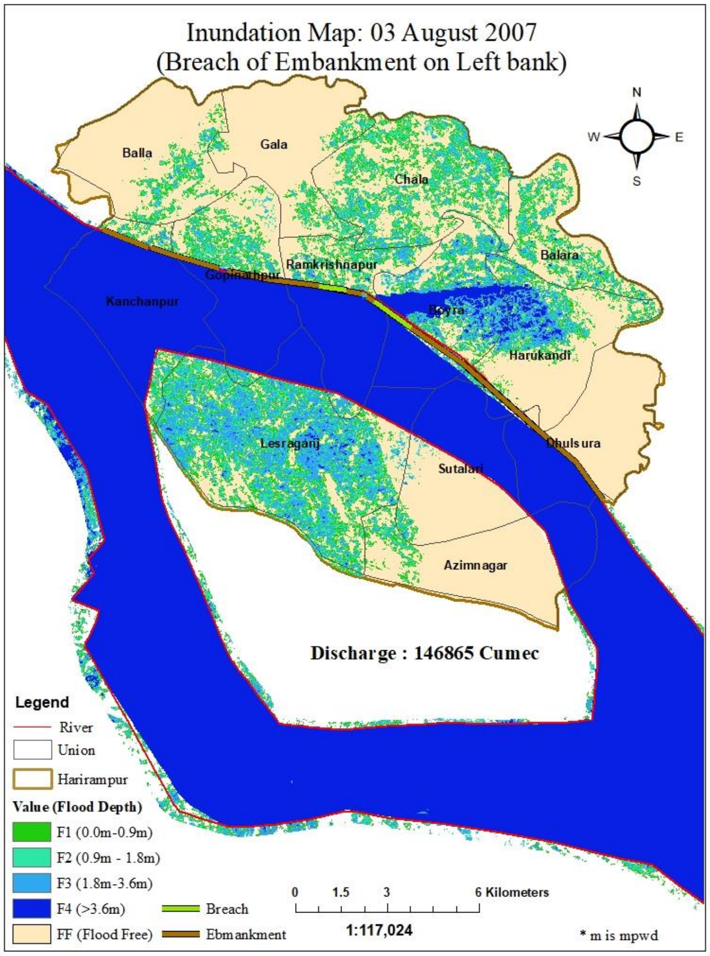

Figure 7-6: Flood Inundation map for 03 August 2007 with Breaching of proposed Embankment on the Left Bank of the Padma River

7.8 Flood inundation results analysis both inclusive and exclusive of river area

Comparison was made using the results produced from model results under four different scenarios, it could be concluded that **scenario two (with full flood control embankment)** was the best situation and results maximum flood free land and minimum flood inundation areas with relative less depths. Therefore, development of flood hazards and management would be easy in this scenarios. Implementation of flood control and mitigation measures were quite feasible.

The worst scenario was **scenario one (no control measures are being implemented)** results maximum flood inundation in different depths as well as flood extent which developed more flood hazards causes damages to standing agricultural crops, fisheries, water and sanitation, socio-economic livelihoods and facilitate river erosion so the management of Hazards would be most difficult. This would increase miseries and suffering of the local people and seriously impacted the livelihood of the local people.

It is to be noted here that the scenarios four (embankment breaching at two specific locations) was relatively better than that of scenarios three (Embankment overtopping by flood flow) due to less inundated area, provided protection of little more area than that of scenarios three. Hazard would be relatively less in case of scenarios four and duration of hazard would also not be continued for longer period.

Flood Inundation Analysis without River area: The total area of Harirampur has been divided into left Bank 121.80 km^2 (mainland); right bank area 59.35 km^2 (Charland) and river areas 62 km^2 as identified from the GIS map. Attempt was made to explore the changes to be taken place in areas of left side of river bank(10 unions) and areas right side of Padma river bank in char lands (3 unions) of Harirampur. This changes in both left bank side and right bank side (charland) were identified separately from the model results for peak flood of year 2007. Table 7-7and Table 7-8, clearly defined land areas in each class (F1, F2, F3, F4 and FF). The inundation area consists of land areas fell under F1-F4 and flood free land falls under FF class for all four scenarios. This analysis was made considering land areas in left bank and right bank in char lands separately for both flooding conditions.

Peak Flood of year 2007

Information from the Table 7-7 (left bank main land) and Table 7-8 (right bank char lands) indicates flooding in left bank area was maximum 59.02 km^2 in **scenario four** (Embankment breaching) and the flooding area is minimum 21.62 km^2 in **scenario two** (full flood control embankment at left bank). Similarly the flood free area is maximum in **scenario two** 100.62 km^2 and flood free land is minimum 62.79 km^2 for the **scenarios four** (Embankment breaching)**.** It is to be mentioned here that river area has not been considered in this calculation. The char land located in the right bank of river, the maximum flooded area is 28.77 km^2 under the **scenario two** (full flood control embankment at the left bank) while minimum flooded area is 28.75 km^2 for the **scenarios one** (without flood control embankment in the left bank). The flood free areas is 30.60 km^2 equal for all scenarios.

Table 7-7: Inundation area at different depths for left bank side (main land) excluding river area

Scenario		**Left Bank Area Inundated (km^2) exclusive of river areas**				
	FF (Flood Free)	**F1(0.0m-0.9m)**	**F2(0.9m-1.8m)**	**F3(1.8m-m-3.6m)**	**F4(>3.6m)**	**Inundated Area**
Scenario 01 (Without Embankment)	67.00	17.27	16.98	19.04	1.51	54.80
Scenario 02 (Proposed Embankment)	100.18	7.70	9.14	4.67	0.11	21.62
Scenario 03 (Overtop of Embankment)	73.14	17.02	15.17	12.39	4.09	48.67
Scenario 04 (Breach of Embankment)	62.79	32.78	12.93	9.43	3.88	59.02

Table 7-8: Inundation area at different depth for right bank side (char land) excluding river area

		Char Area Inundated (km^2) area on the right bank				
Scenarios description	**FF (Flood Free)**	**F1(0.0m-0.9m)**	**F2(0.9m-1.8m)**	**F3(1.8m-3.6m)**	**F4(>3.6m)**	**Inundated Area**
Scenario 01 (Without Embankment)	30.60	7.74	9.48	11.10	0.43	28.76
Scenario 02 (Proposed Embankment)	30.59	7.54	9.69	11.11	0.43	28.77
Scenario 03 (Overtop of Embankment)	30.60	7.74	9.48	11.11	0.43	28.76
Scenario 04 (Breach of Embankment)	30.60	7.53	9.69	11.11	0.43	28.76

7.9 Flood Hazards in the study area

There are different types of hazards occurred due to flooding. The flooding hazards listed are i) river erosion; ii) crop damage; iii) damage to fish ghers; iv) damage of fruit trees; v) communication disruptions; vi) damage to communication infra-structures; vii) drowned of drinking water tube well and its platform as well; viii) sanitation problem; ix) damage to grazing land for livestock; x) home stead inundation; xi)waterborne disease; xii) disease outbreak of poultry and livestock; xiii) damage to wealth and resources; xiv) job crises for daily workers, labors and farmers; xv) crises of fuel woods; xvi) increase of poverty; xvii) damage to education systems; xviii) rural remotely schools and education system remain closed; xix) deterioration of livelihood of local poor people; xx) food hunger and xxi) damage to rural ecosystems.

7.10 Development of Hazard Map of Harirampur

Flood Hazard Map was important outcome and prepared using the results from the scale of hazards in each union considering the impacts of the flood inundations. Each union of Harirampur impacted by one or more hazards on the basis of depth of flooding and its extent and duration until clear out the flood water. This map was ground troughed with local stakeholders through application of the social tools such as FGD, KII and random discussion with local knowledgeable people during the visit of the Harirampur.

7.11 Administrative Unit for Hazard Mapping

Bangladesh is divided into 8 (eight) Divisions and 64 Districts, although these have only a limited role in public policy. For the purposes of local government, the country is divided into upazilla, municipalities, city corporations and union.

In this study, upazilla administrative units had been considered. There were 13 (thirteen) unions in the study area in administrative unit map of Harirampur shown in Figure 7-7. Based on this map, four types of Hazard Maps under four different scenarios described earlier were developed for the flood of 03 August 2007.

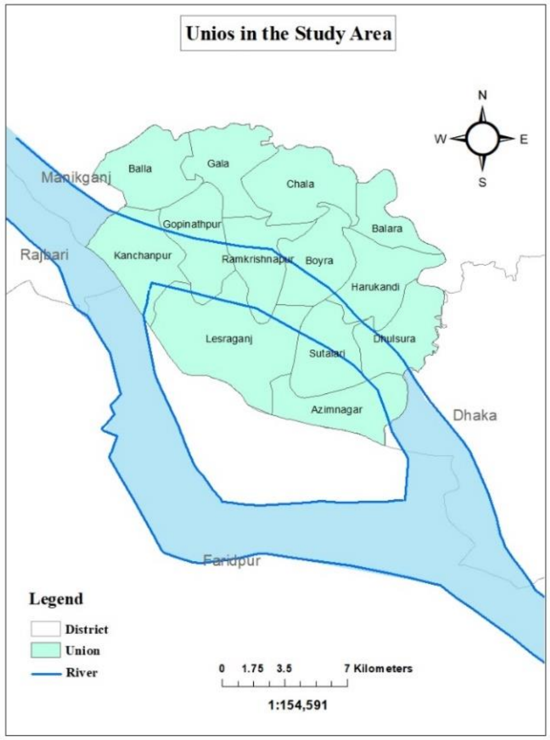

Figure 7-7: Map showing the boundary of administrative union of the study area

7.12 Flood Hazard Mapping of Harirampur for 2007 year flood

7.12.1Flood Hazard Mapping on Scenarios 1(without any Flood control embankment but inclusive of river area)

This scenario was the most as usual scenario without any engineering protection by flood control embankment where area was found under FF (Flood free land) is 99.51 km^2 about 41% of total land area of Harirampur upazilla. The total land area inundated under different flood depths F1, F2, F3 and F4 is 143.55 km^2 only was about 59.06%. The union wise flood hazard ranked map shown in Figure 7-8. From the map, it is seen that unions Kanchanpur is in Very High Hazard Rank (HR4), while Gopinathpur, Ramkrishnapur, Boyra and Laserganj unions are in the High Hazard Rank(HR3), Azimnagar Balla, Chala, Dulsura and Sutalari unions are in Medium Hazard Rank (HR2) and union are in Less Hazard ranking are Gala, Harukandi and Balara.

Almost all above mentioned hazards are be occurred under this scenario in HR4, unions of the Harirampur which were near the mighty Padma River. Relatively less no of hazards took place in other unions which were in HR3, HR2 and less no of Hazards would be taken place in unions of HR1.

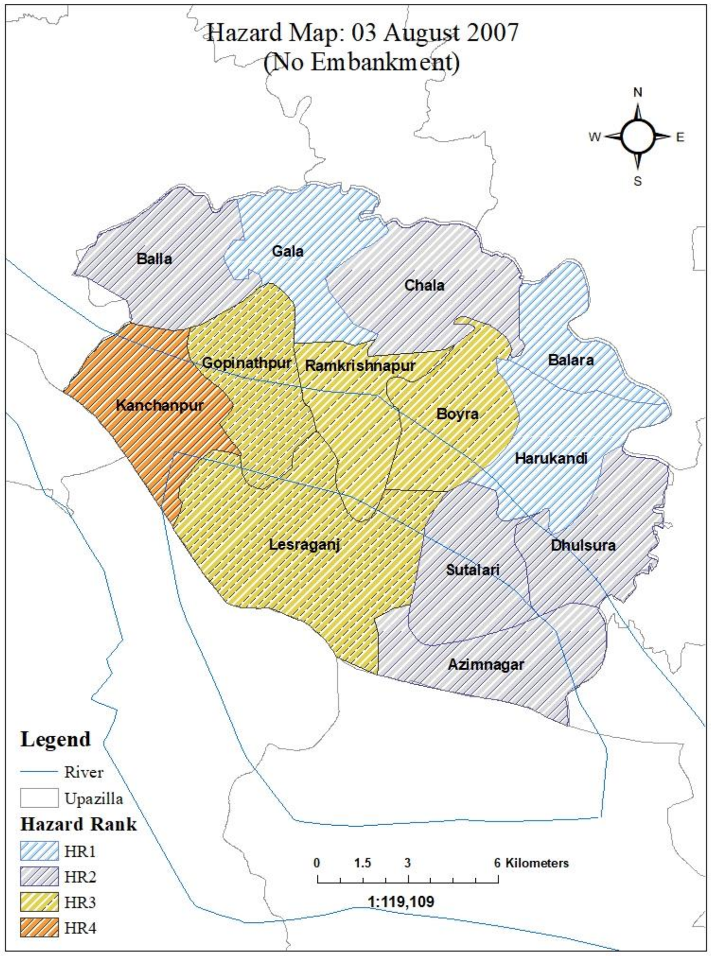

Figure 7-8: Hazard map without any embankment in the left bank of the Padma River for 03 August 2007 inclusive of river area.

7.12.2 Flood Hazard Mapping for Scenarios two (with full flood control embankment)

This scenario presents the optimistic situation as assumed to be implemented of proposed 17 km full Flood Control Embankment where maximum area out of four scenarios was found under FF (Flood free land) is 132.89 km^2 about 54.67% of total land area of Harirampur upazilla. The total land area under different flood depths F1, F2, F3 and F4 is 110.17 km^2 only was about 45.33%. Flooding would only be occurred due to rainfall runoff which results water stagnation at various locations.

The Flood Hazard Map showed in Figure 7-9 that Kanchanpur union was in the HR4, while Gopinathpur Ramkrishnapur Laserganj and Sutalari unions were in the HR3, Boyra, Azimnagar and Dulsura unions were in HR2 and Balla, Chala, Gala and Harukandi unions were in HR1. It was noticeable that only one union Balara where no flood was occurred.

Relatively less no of hazards mentioned above would be occurred under this scenario in HR4, unions of the Harirampur which were near the mighty Padma River as the areas were fully protected by embankment. Also less hazard would be occurred in other unions which were in HR3, HR2 and less no of Hazards will be occurred in unions in HR1.

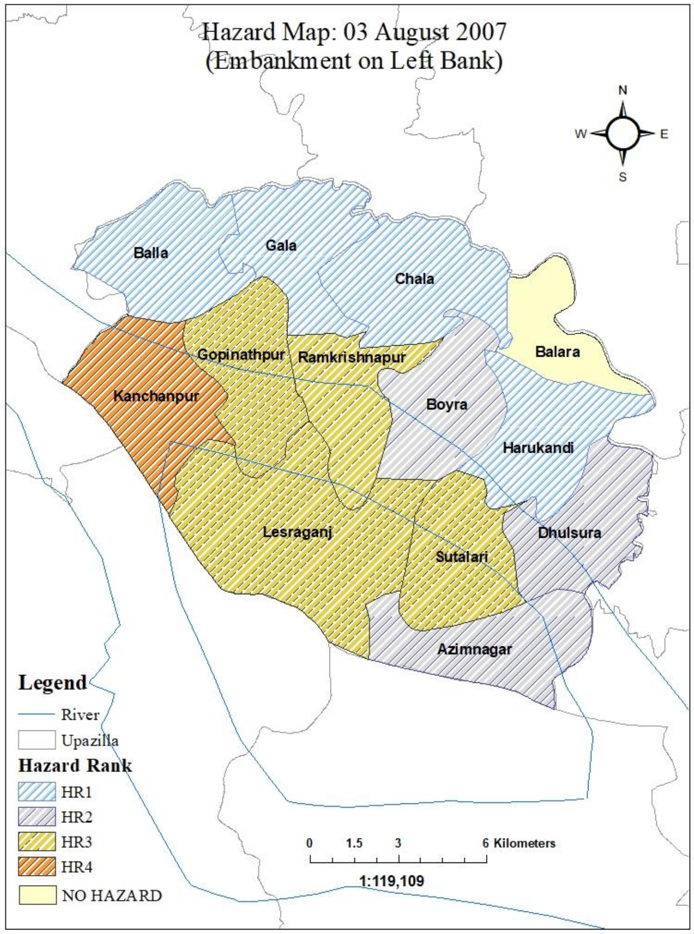

Figure 7-9: Hazard map for the proposed Embankment at the left side of the Padma River on 03 August 2007.

7.12.3 Flood Hazard Mapping on Scenarios 3 (Overtopping of Embankment)

This the scenario where full flood control embankment provides the protection up to certain level of flood (embankment crest level) and when the flood cross the embankment crest level overtop the embankment uniformly and flood water inundation would be occurred. The area found under FF (Flood Free Land) was 105.61km^2 about 43.45% of total land area of Harirampur. The total land area under different flood depths F1, F2, F3 and F4 is 137.45 km^2 only is about 57%. Flooding would be occurred due to rainfall runoff and flood extents would be increased when flood water that comes due to overtopping of flood control embankment crest level.

The Flood Hazard Map showed in Figure 7-10 that Kanchanpur union was in HR4 , while Gopinathpur Ramkrishnapur Laserganj, Boyra and Sutalari unions were in HR3, Azimnagar and Dulsura unions were in HR2 and unions were in HR1 are Balla, Chala, Gala, Balara and Harukandi.

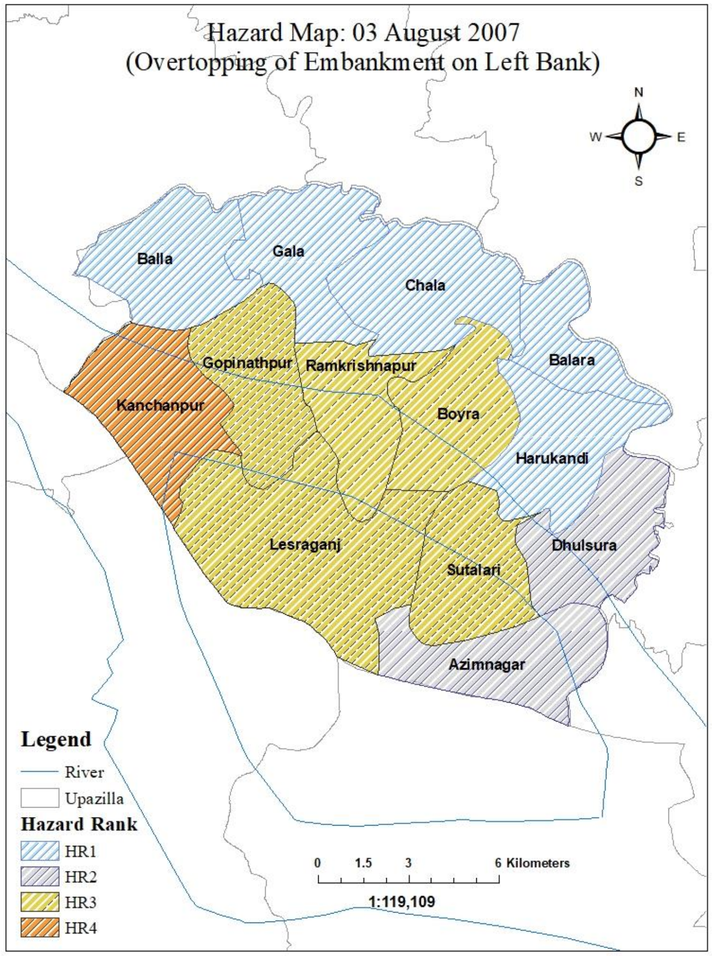

Figure 7-10: Hazard map for overtopping of left bank Embankment by flood flow on 03 August 2007

7.12.4Flood Hazard Mapping on Scenarios 4 (Breaching of Embankment)

This the scenario where full flood control embankment will provide the protection but the flood water inundation would be occurred due to breaching of embankment in two locations such as about 3.5 km length (1km at location of Gopinathpur and 2.5 km at location at Andharmanik all together in two different locations).

In this scenarios the area was found under FF (Flood Free) is 113.21km^2 about 46.58% of total land area of Harirampur. The total land area under F1, F2, F3 and F4 (no land under this category) was about 129.85 km^2 which was 53.42 % of total area. Flooding would be occurred both due to rainfall runoff and flood water entered through breaching of embankments at two locations respectively.

The Flood Hazard Map shown in Figure 7-11 that unions Kanchanpur and Laserganj were in HR4. While Gopinathpur, Ramkrishnapur and Boyra unions were in HR3, and union in HR2 were Sutalari, Dulsura, Harukandi and Azimnagar. The unions in HR1 were Balla, Gala, Chela and Balara unions. The flooding results more or less similar for both scenarios 3 and 4 with small change of areas. Little more area in FF class was found in scenarios 4 than that of scenarios 3. However this also affected flooding extent as well with small change.

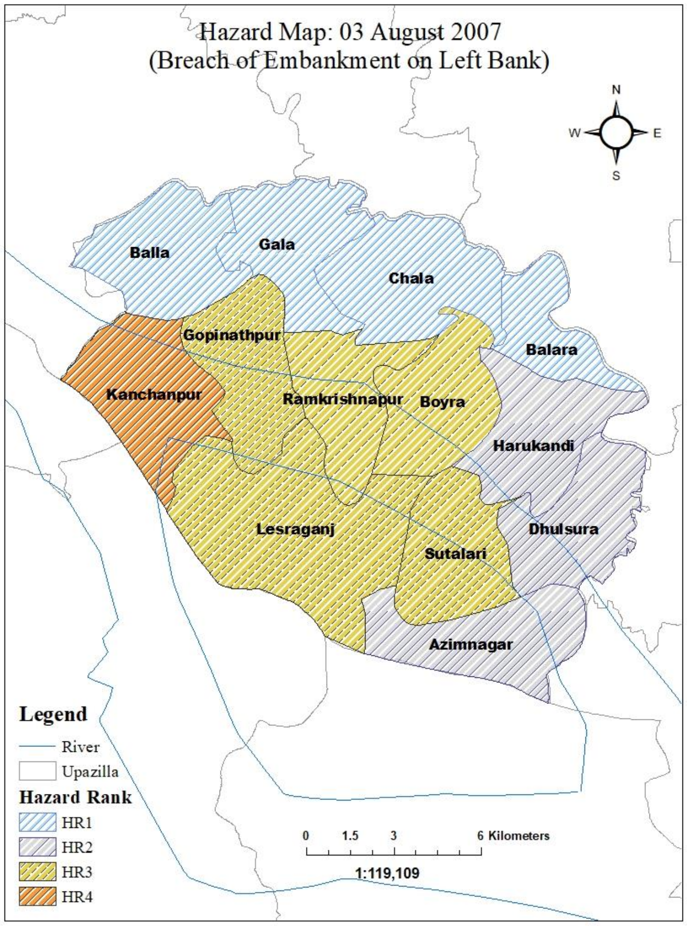

Figure 7-11 Hazard map for Breaching of Embankment on the Left Bank on 03 August 2007.

Table 7-9: Administrative Boundary wise (Union) Hazard ranking in Harirampur for four different scenarios on flood of 03 August 2007

Union Name	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Balla	2	1	1	1
Kanchanpur	4	4	4	4
Gala	1	1	1	1
Chala	2	1	1	1
Balara	1	0	1	1
Dulshura	2	2	2	2
Ramkrishnapur	3	3	3	3
Gopinathpur	3	3	3	3
Lesraganj	3	3	3	3
Sutalari	2	3	3	3
Azimnagar	2	2	2	2
Harukandi	1	1	1	2
Boyra	3	2	3	3

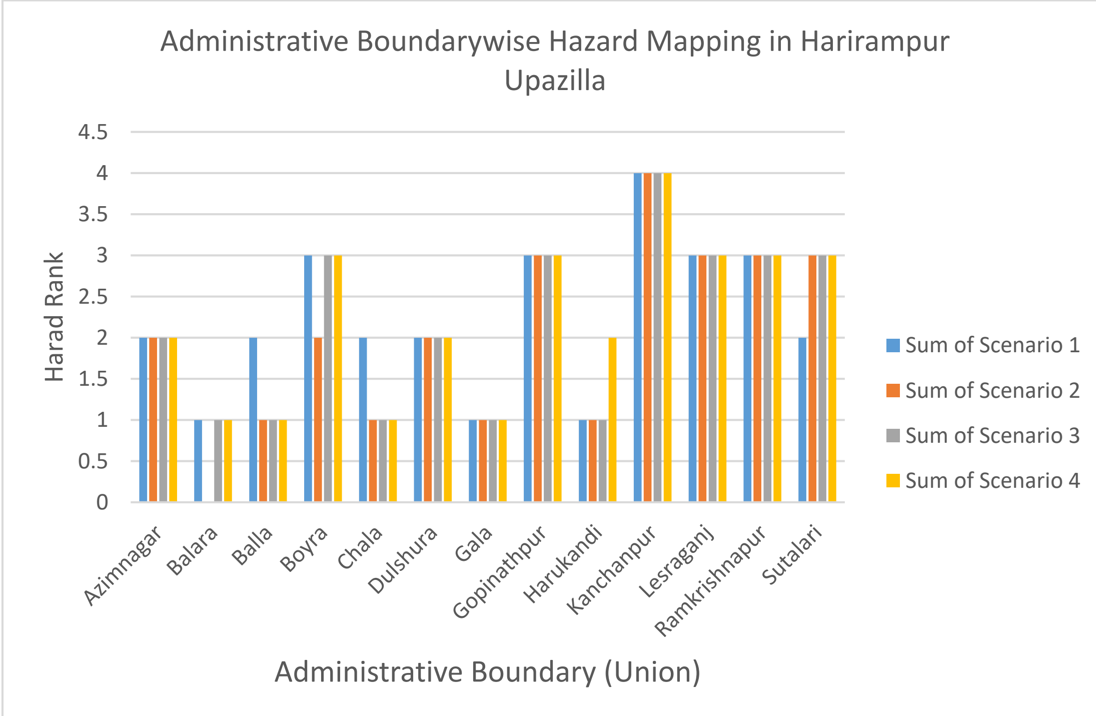

Figure 7-12: Administrative Boundary wise (Union) Hazard Ranking in Harirampur upazilla for four different scenarios on 03 August 2007.

From the table 7-9 and figure 7-12 it was found that the hazard rank of unions remain same for all scenarios are Kanchanpur, Gala, Dhulsura, Ramkrishnapur, Gopinathpur, Lesarganj and Azimnagar. Other union's hazard rank are changed different for different scenarios.

7.13 Model Application for flood of 100 year return period

7.13.1Flood Inundation Depth and Extent Analysis (inclusive of river areas)

Applied model yielded inundation area and percentage under four different scenarios as described earlier. The Table 7-10 shows inundation extent at different flood depth while Table 7-11 shows Percentage of Inundation areas to total areas respectively.

7.13.2 Scenario 1 (without any flood control embankment)

In this scenario, model generated flood extent and inundation map of Harirampur upazilla which consists of thirteen unions. Significant part of land of Balara, Harukandi, Dhulshura and Sutalari, Azimnagar, Lesarganj (partly) were under flood free (FF). And remaining lands in other unions including above mentioned unions were in mixed distribution such as 10.45% land in F1 and 11.75% land in F2. While 15.78% land in F3, 26.92% land in F4. Almost 35.11% land area is flood free and the total flood inundation area is 64.89%. Flood Inundation extent and flood depth map shown in Figure 7-13.

Table 7-10: Inundation depth and extent under four different scenarios of flood for 100 year return period inclusive of the Padma river areas

			Area Inundated (km^2)					
	Scenarios descriptions	FF (Flood Free)	F1 (0.0-0.9m)	F2 (0.9-1.8m)	F3 (1.8-3.6m)	F4 (>3.6m)	Inundated area (F1-F4)	Total area
Model Scenarios	Scenario 01 (Without Embankment)	85.34	25.39	28.55	38.35	65.43	157.72	243.06
	Scenario 02 (Proposed Embankment)	98.25	23.14	28.86	29.54	63.27	144.81	243.06
	Scenario 03 (Overtop of Embankment)	81.06	28.04	31.16	38.64	64.17	162.01	243.06
	Scenario 04 (Breach of Embankment)	92.06	21.65	28.87	36.99	63.50	151.00	243.06

Table 7-11 Percentage of Inundation extent to total area of Harirampur for four different scenarios for 100 year flood inclusive of the Padma river areas

	Name of Scenarios	**FF (% area)**	**F1 (% area)**	**F2 (% area)**	**F3 (% area)**	**F4 (% area)**	**% of Inundation**
Model Scenarios	Scenario 01 (Without Embankment)	35.11	10.45	11.75	15.78	26.92	64.89
	Scenario 02 (Proposed Embankment)	40.42	9.52	11.87	12.15	26.03	59.58
	Scenario 03 (Overtopping of Embankment)	33.35	11.54	12.82	15.90	26.40	66.65
	Scenario 04 (Breach of Embankment)	37.87	8.91	11.88	15.22	26.12	62.13

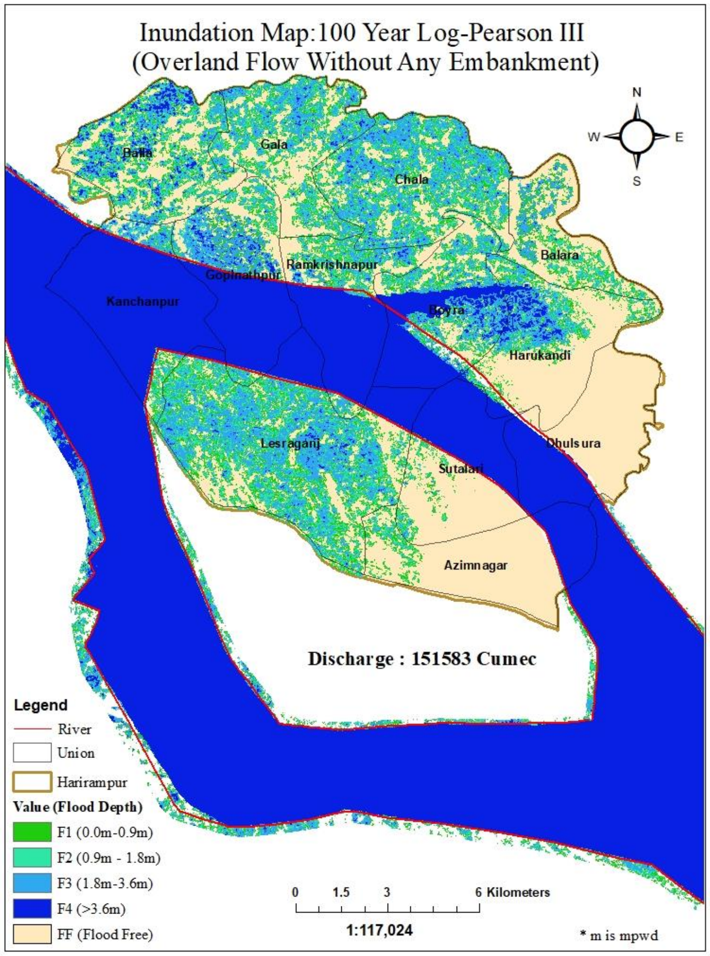

Figure 7-13: Flood Inundation map of 100 year return period without any flood control embankment.

7.13.3 Scenario 2 (with full flood water control infrastructures):

This was the best scenario and full protection given by 17 km of flood control embankment in the left bank of the Padma River. Model generated flood extent and inundation map of Harirampur. Significant part of land of Balla, Gala, Chela, Boyra, Balara, Harukandi, Dhulshura and Sutalari, Azimnagar, Lesarganj (partly) was remained as flood free (FF). And remaining lands in other unions including the above mentioned unions were in mixed distribution such as 9.52% land in F1 and 11.87% land in F2. While 12.15% land in F3, 26.03% land in F4. In all the scenarios, three unions of Harirampur falls fully within the river conveyance in F4 land and that was why percentage of land in F4 was maximum in every scenarios. It was to be mentioned here that inundation extent in different depth during wet seasons were due to overland flow gradually moving to the river and accumulated in different parts of the ten of the Harirampur.

Almost 40.42% land area which is the maximum of all scenarios is flood free and the total flood inundation area is 59.58%. Flood Inundation extent and flood depth map shown in Figure 7-14.

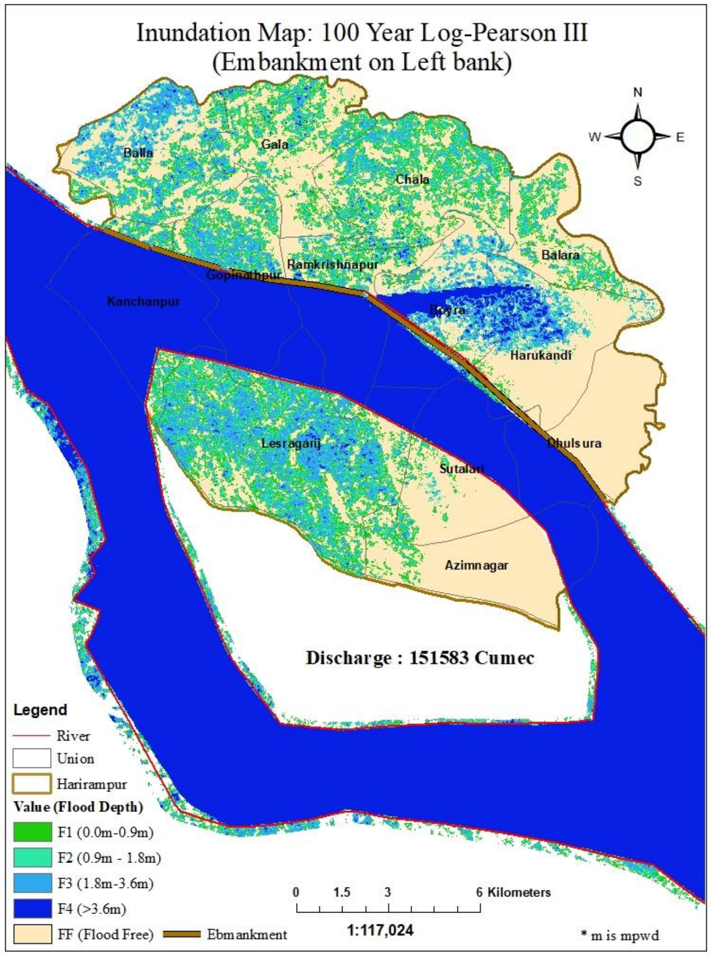

Figure 7-14: Flood Inundation map for full flood control by Embankment at the left side of the Padma River for flood of 100 year return period.

7.13.4 Scenario 3 (Overtopping of full flood control embankment):

In this scenario, it was assumed that flood flow would overtop the embankment crest uniformly of 17km embankment and flood water would entered in the left bank side unions of Harirampur. The model generated flood extent and inundation map of Harirampur upazilla. Significant part of land of Harukandi, Sutalari, Dhulshura, Azimnagar, Lesarganj was flood free (FF). And remaining lands in other unions including the above mentioned unions were in mixed distribution in different flood depth such as 11.54% land in F1 and 12.82% land in F2. While 15.90% land in F3, 26.40% land in F4. Almost 33.35% land area was flood free and the total flood inundation area is 66.65%. Flood Inundation extent and flood depth map shown in Figure 7-15.

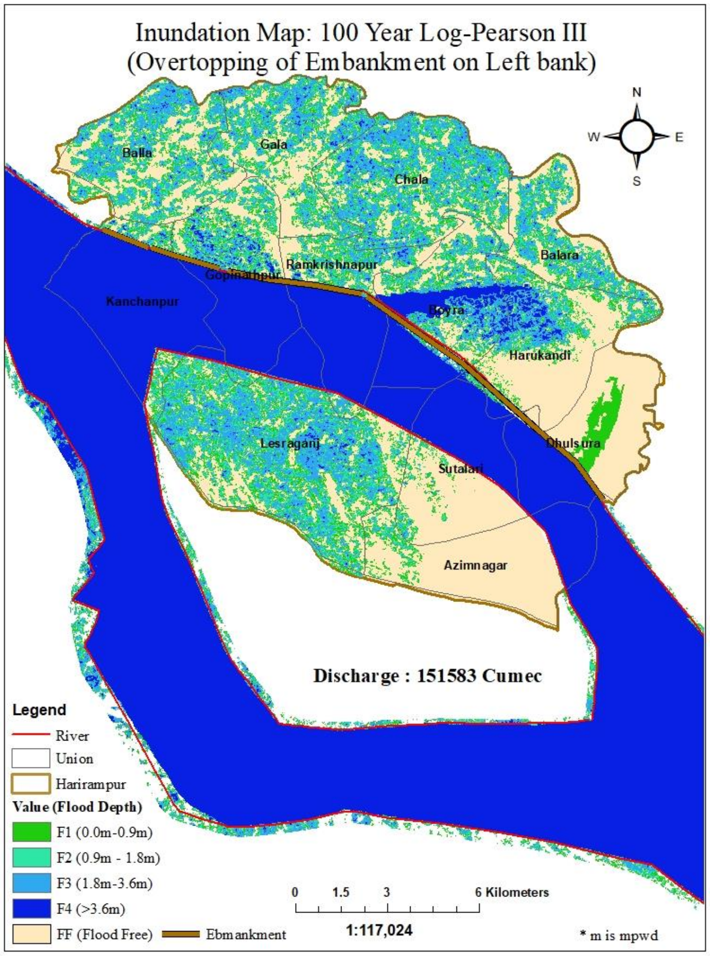

Figure 7-15: Flood Inundation map for 100 year return flood with overtopping of Embankment on the Left Bank the Padma River

7.13.5 Scenario 4 (Breaching at two locations of full flood control embankment):

In this scenario, it was assumed that breaching of flood embankment would be occurred at two locations (one location was at Gopinathpur of 1km breach while the other was at Andermanik, Boyra of 2.5 km in length and total length of breaching was in total 3.5 km. The model generated flood extent and inundation map of Harirampur upazilla for all the thirteen unions. Significant part of land of Balla, Gala, Harukandi, Dhulshura, Sutalari and Azimnagar, were flood free (FF). And remaining lands in other unions including the above mentioned unions were in mixed distribution such as 8.91% land in F1 and 11.88% land in F2. While 15.22% land in F3, 26.12% land in F4.

Almost 37.87% land area which was maximum in all scenarios was flood free and the total flood inundation area is 62.13%. Flood Inundation extent and flood depth map shown in Figure 7-16.

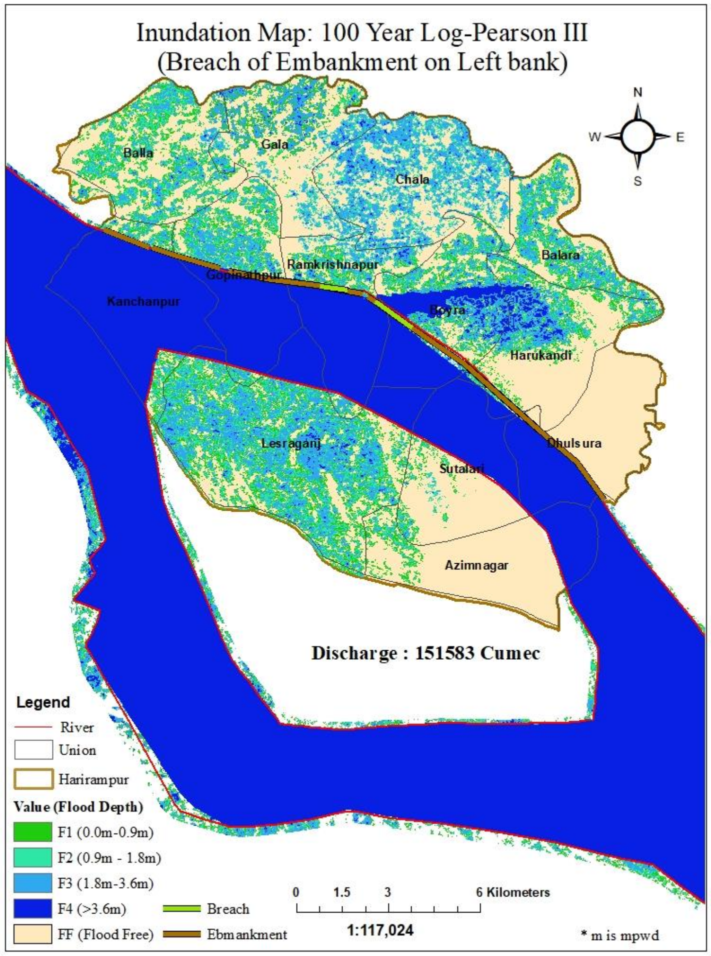

Figure 7-16: Flood Inundation map for flood of 100 year return period with breaching of embankment on the left bank of the Padma River

7.14 Comparison of Flood Inundation including and excluding the Padma River

Comparison was made among all the maps produced from model results under four different scenarios, it could be concluded that **scenario two (with full flood control embankment)** was created relatively best hydro-morphological situation and results maximum flood free land and relatively minimum flood inundation areas with relative less depths. Therefore, development of flood hazards and management hazard would be easy. Therefore implementation of flood control and mitigation measures were quite feasible.

The worst scenario was **scenario one (no control measures are being implemented)** results maximum flood inundation depth as well as flood extent which developed more flood hazards causes damages to standing crops, fisheries, water and sanitation, socio-economic livelihoods and facilitate river erosion so the management of Hazards would be most difficult. This would increase miseries and suffering of people and seriously impacted the livelihood of the local people.

However**, scenarios three (Embankment overtopping by flood flow)** was relatively better than that of **the scenarios four (embankment breaching at two specified location)** as scenarios three provided protection of more area than that of scenarios four. Hazard would be relatively much less in case of scenarios three and duration of hazard would also not be continued for longer period.

Flood Inundation Analysis without River area

Information from the Table 7-12 and 7-13 indicates flooding in left bank area is maximum is 72.16 km^2 for **scenario three** (overtopping embankment) while flooding area minimum 54.97 km^2 in **scenario two** (full flood control embankment at left bank). The flood free area maximum 66.83 km^2 in **scenario two** and flood free land is minimum 49.65 km^2 in the **scenarios three** (overtopping embankment). But **scenario four** (Breaching) flood free areas was more and inundation areas was less than **scenarios three,** river areas was considered in this analysis.

Table 7-12: Inundation area at different depth for left bank side (main land) for 100 year return period of flood excluding river area

Scenario description	**Left Bank Area Inundated (km^2) exclusive of river areas**					
	FF (Flood Free)	**F1(0.0m-0.9m)**	**F2(0.9m-1.8m)**	**F3(1.8m-m-3.6m)**	**F4(>3.6m)**	**Inundated Area**
Scenario 01 (Without Embankment)	53.93	16.75	18.14	26.39	6.60	67.88
Scenario 02 (Proposed Embankment)	66.83	14.59	18.35	17.59	4.44	54.97
Scenario 03 (Overtop of Embankment)	49.65	19.35	20.76	26.71	5.34	72.16
Scenario 04 (Breach of Embankment)	60.71	13.03	18.36	25.04	4.67	61.10

The char land located in the right bank of the river, the maximum flooded area was 29.60 km^2 under the **scenario four** (breaching of flood control embankment in the left bank) while minimum flooded area is 29.53 km^2 for scenarios **three** (embankment overtopping) and **scenario two** (with flood control embankment) in the left bank. It is to be mentioned here that river area has not being considered in this calculation. It was mentioned here that inundation area falls in right not changed at all in both flooding in 2007 and 100 year flood in all the four scenarios.

Table 7-13: Inundation area at different depth for right bank side (char land) for 100 year return period of flood excluding river area

Scenarios description	Char Area Inundated (km²) area on the right bank					
	FF (Flood Free)	**F1(0.0m-0.9m)**	**F2(0.9m-1.8m)**	**F3(1.8m-3.6m)**	**F4(>3.6m)**	**Inundated Area**
Scenario 01 (Without Embankment)	29.83	8.12	9.80	11.18	0.44	29.53
Scenario 02 (Proposed Embankment)	29.80	8.05	9.91	11.17	0.43	29.56
Scenario 03 (Overtop of Embankment)	29.83	8.12	9.81	11.17	0.43	29.53
Scenario 04 (Breach of Embankment)	29.76	8.05	9.93	11.18	0.44	29.60

7.15 Development of Hazard Map of Harirampur for 100 year flood

Flood Hazard Mapping of Harirampur under each scenarios for flood of 100 year return period were discussed as below:

7.15.1 Flood Hazard Mapping on Scenarios 1 (without any flood control embankment) inclusive of river area

This scenario was the most as usual scenario without any engineering protection where area was found under FF (Flood free land) 85.34 km^2 about 35.11% of total land area of Harirampur upazilla. The total land area under different flood depths F1, F2, F3 and F4 was 157.72km^2 only about 64.89%. The union wise flood hazard ranked map shown in Figure 7-17.

From the map, it was seen that unions Kanchanpur and Gopinathpur were in HR4, while Ramkrishnapur, Boyra, Sutalari and Lesarganj unions were in HR3, Balla, Chala, Gala, Harukandi, Azimnagar and Dulsura unions were in HR2 and union in HR1 was Balara.

Almost all above mentioned hazards be occurred under this scenario in HR4, unions of the Harirampur which were near the mighty Padma River. Relatively less hazard took place in other unions which were in HR3, HR2 and less no of Hazards would be taken place in unions of HR1.

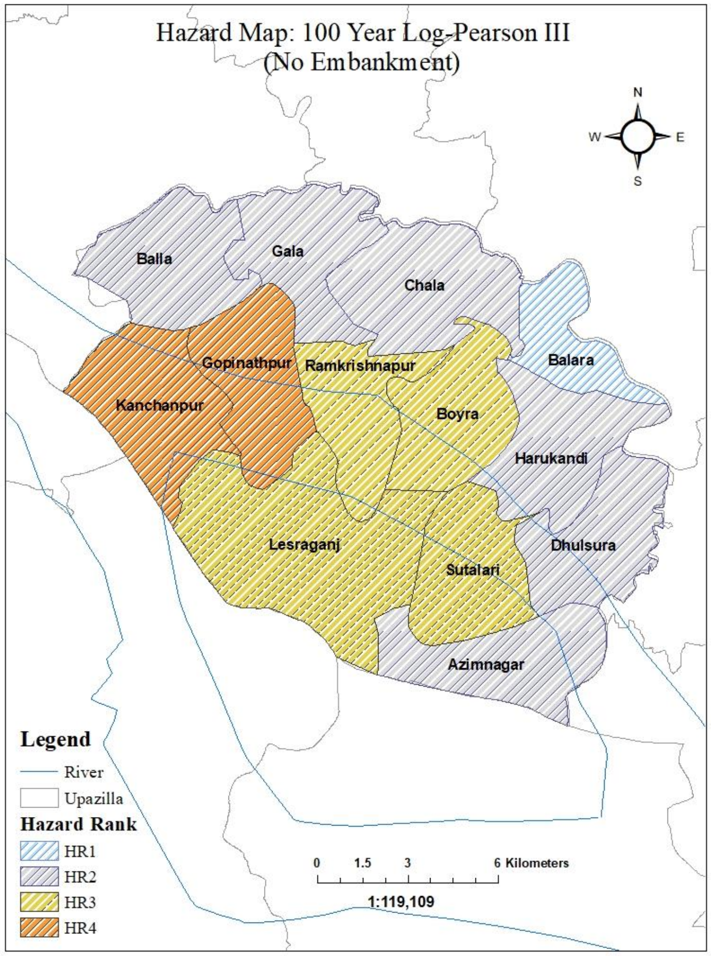

Figure 7-17: Hazard map for flood of 100 year return period without any Embankment in the Padma River

7.15.2 Flood Hazard Mapping on Scenarios 2(with Full Flood Embankment)

This scenario presents the optimistic situation due to implementation of proposed 17 km full Flood Control Embankment would be constructed where maximum area out of four scenarios was found under FF (Flood free land) is 98.25 km^2 about 40.42% of total land area of Harirampur upazilla. The total land area under different flood depths F1, F2, F3 and F4 is 144.81km^2 only was about 59.58%. Flooding would only be occurred due to rainfall runoff which results water stagnation at various locations.

The Flood Hazard Map showed in 7-18 that Kanchanpur union was in HR4 while Gopinathpur Ramkrishnapur Laserganj, Boyra, and Sutalari unions were in HR3, Balla, Azimnagar and Dulsura unions were in HR2 and unions in HR1 were Chala, Gala, Balara and Harukandi.

Relatively less no of hazards mentioned above would be occurred under this scenario in HR4 unions of the Harirampur which were near the mighty Padma River as the areas were fully protected. Also less hazard would be occurred in other unions which are in HR3, HR2 and less no of Hazards will be taken place in unions of HR1.

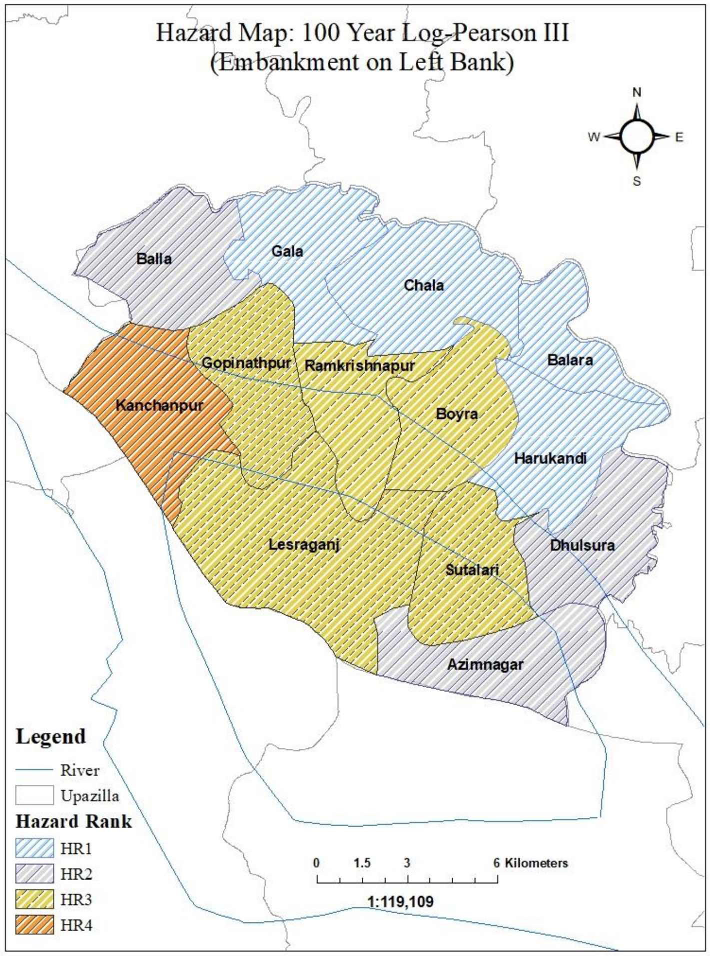

Figure 7-18: Hazard map for Embankment at the left side of the Padma River for 100 year return period.

7.15.3 Flood Hazard Mapping on Scenarios 3 (Embankment overtopping)

This the scenario where full flood control embankment provides the protection up to certain level of flood (embankment crest level) and when the flood cross the embankment crest level overtop the embankment uniformly and flood water inundation would be occurred. The area found under FF (Flood Free Land) was 81.06 km^2 about 33.35% of total land area of Harirampur upazilla. The total land area under different flood depths F1, F2, F3 and F4 is 162.01km^2 only is about 66.65%. Flooding would be occurred due to rainfall runoff and flood extents would be increased when flood water that comes due to overtopping of flood control embankment crest level.

The Flood Hazard Map showed in 7-19 that Kanchanpur and Ramkrishnapur union were in the HR4, while Gopinathpur, Laserganj, Boyra and Sutalari unions were in the HR3, Balla, Chala, Azimnagar, Balara, Harukandi and Dulsura unions were in HR2 and unions were in HR1 was Gala.

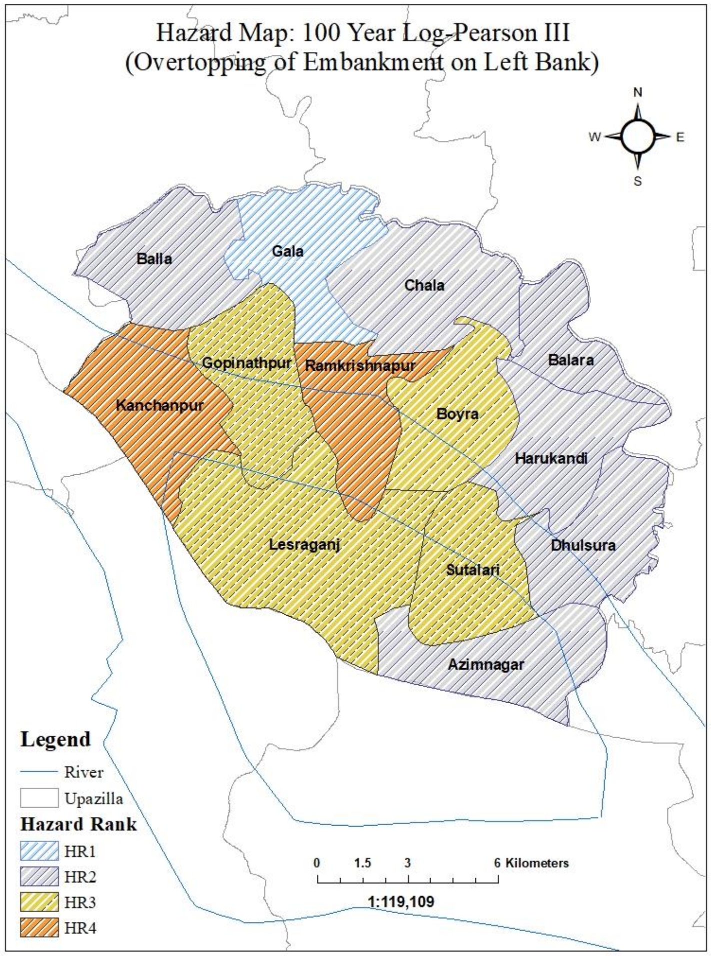

Figure 7-19: Hazard map for overtopping of Embankment by flood flow on the Left Bank the Padma River for flood of 100 year return period.

7.15.4Flood Hazard Mapping on Scenarios 4 (Embankment breaching)

This the scenario where full flood control embankment will provide the protection but the flood water inundation would be occurred due to breaching of embankment in two locations such as about 3.5km length (1.0 km at location of Gopinathpur and 2.5 km at location at Andharmanik all together in two different locations).

In this scenarios the area found under FF (Flood Free) was 92.06 km^2 about 37.87% of total land area of Harirampur. The total land area under F1, F2, F3 and F4 was 151 km^2 which was 62.13% of total area. Flooding would be occurred due to rainfall runoff and flood water entered through breaching of embankments at two locations respectively.

The Flood Hazard Map shown in 7-20 that unions Kanchanpur and Ramkrishnapur were in HR4, while Gopinathpur, Boyra, Laserganj and Sutalari unions were in HR3, and union in HR2 were Balla, Gala, Chala,Balara, Harukandi, Dulsura, and Azimnagar.

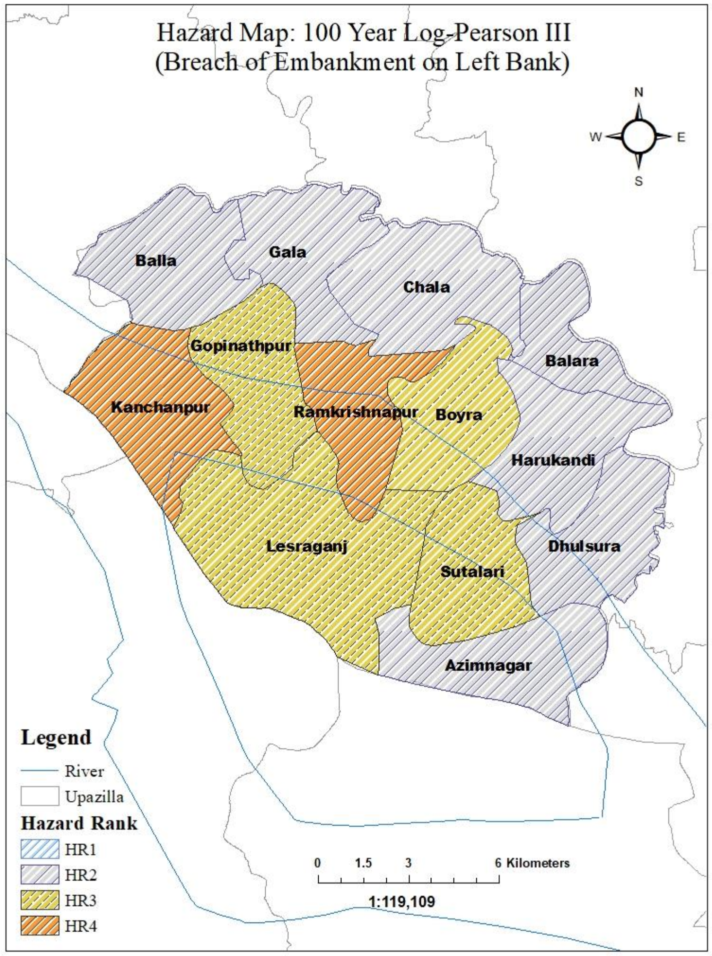

Figure 7-20: Hazard map for Breaching of Embankment on the Left Bank of the Padma River for flood of 100 year return period.

Table 7-14: Administrative Boundary wise (Union) Hazard ranking in Harirampur for the four different scenarios for flood of 100 year return period

Union Name	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Balla	2	2	2	2
Kanchanpur	4	4	4	4
Gala	2	1	1	2
Chala	2	1	2	2
Balara	1	1	2	2
Dulshura	2	2	2	2
Ramkrishnapur	3	3	4	4
Gopinathpur	4	3	3	3
Lesraganj	3	3	3	3
Sutalari	3	3	3	3
Azimnagar	2	2	2	2
Harukandi	2	1	2	2
Boyra	3	3	3	3

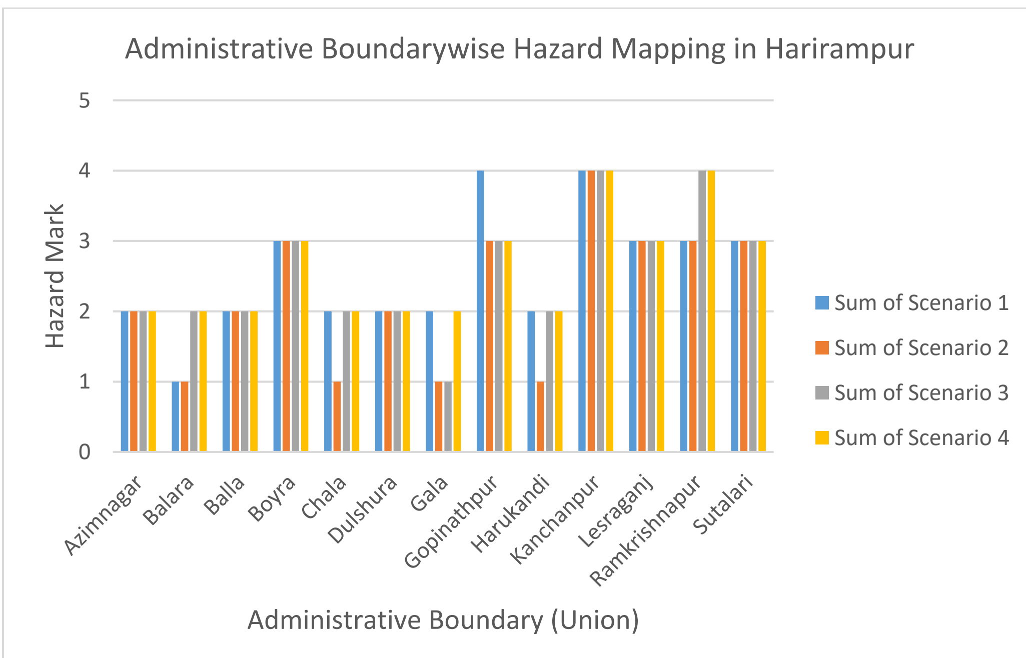

Figure 7-21: Administrative Boundary wise (Union) Hazard Ranking in Harirampur upazilla for four different scenarios for flood of 100 year return period

From the table 7-14 and figure 7-21 it is found that the hazard rank of unions remained same for all scenarios are Kanchanpur, Balla and Azimnagar. Other union's hazard rank are changed from lower to higher for four scenarios.

7.16 Comparison of 100 year Flood with Peak flood of year 2007

It was found that more inundation occurred in the scenarios for flood of 100 year return period than that of peak flood flow of year 2007 (which was flood of more than 50 year return period). In case of flood of 100 year return period, 66.65% and 62.13% area were inundated for the case of scenario 3 (Over-topping of embankment) and Scenarios 4 (Breaching of embankment) respectively whereas 56.55% and 53.42% areas were inundated for the case of scenario 3 and Scenarios 4 respectively for flood year 2007.

Comparison of hazard maps for overtopping and breaching scenarios were made to see the changes of hazards rank in each unions. Among the 13 unions, 6 unions (Balla, Gala, Chala, Balara, Ramkrishnapur and Harukandi) in Table 7-15 showed change in the hazard ranking in between overtopping (scenario 3) and breaching (scenario 4) for 2007 flood and flood of 100 years return period.

Table 7-15: Comparison of hazard ranking for the over-topping and breaching of embankment in case of peak flood of year 2007 and flood of 100 years return period

Administrative Unit(Union)	Peak Flood of year 2007		Flood of 100 years return period	
	Scenario 3	Scenario 4	Scenario 3	Scenario 4
Balla	1	1	2	2
Gala	1	1	1	2
Chala	1	1	2	2
Balara	1	1	2	2
Ramkrishnapur	3	3	4	4
Harukandi	1	2	2	2

Hazard rank comparison between 2007 Flood and 100 year Flood for scenario 3(overtopping)

The hazard rank of the Unions Balla, Gala, Chala and Balara would be changed from HR1 to HR2 while Ramkrisnapur would be changed from HR3 to HR4. But the union Harukandi would remain same in HR2

Hazard rank comparison for Flood of 2007and Flood of 100 year return period under scenarios 4 (breaching)

The hazard rank of the Unions Balla, Gala, Chala Balara and Harukandi would be changed from HR1 to HR2 while Ramkrisnapur would be changed from HR3 to HR4. But the union Gala would remain same in HR2.

7.17 Field findings on Flood Impacts and Hazards

Among the 13 unions, the stakeholders confirmed that 10 unions were located on the left bank of the Padma River and other three unions (Lesarganj, Sutalari and Azimnagar) were acknowledged that these three unions are located in the charland in the Padma River. Stakeholders provided information, ITK and judgment in hazard ranking and opinion for the measures to improve the river function and protecting their area from flood impacts.

Water Resources System and beels

The Padma, Kaliganga, Ichamati and Old Dhaleshwari River are the main rivers in Harirampur upazilla. A number of connecting canals, beels, ponds and other wetlands are replenished by overland flow and also direct flow from the connecting rivers. Vaatshala beel and Ghurilpul Beel are the noteworthy wetlands in this area. A number of lives are affiliated with these wetlands.

River Erosion Affected

Along the left bank of the Padma River, stakeholders classified that six unions are severely affected by the river flood and erosion as per the current scenario victims are being washout situation. The Kanchanpur, Ramkrishnapur and Gopinathpur were referred at the highest in loss of land by river erosion. Almost 80-90% areas of these unions already eroded in the Padma River within last twenty years. Only two or three villages out of almost 10/12 villages existed of each of the above-mentioned three unions on the bankside of the river. Currently, the Boyra and Dulsura union are vulnerable to erosion.

River Flood affected and Hazard Ranking

In the RRA sessions, stakeholders opined that the devastating flood was occurred in the year 1988 inundated the maximum areas while in 1998 flood was lasted longest time of about one and half month. However, the flood of 2007 prolonged 25-30 days and submerged all the areas including homesteads whose levels are relatively low.

Chala, Gala, Balla, Balara, Harukandi unions are comparatively less affected unions. In the char areas, Sutalari, Lesarganj and Azimnagar became more or less affected by flood over the past decades. But Lesarganj was comparatively more affected than that of other unions in the char.

According to people’s perception in both the situation either overtopping and breaching, Kanchanpur, Ramkrisnapur, Gopinathpur are in the Very High Hazard Ranking (HR4), Boyra, Dulsura, Lesarganj were in High Hazard Rank (HR3), Chala, Gala, Balla, Balara,Harukandi, Sutalari and Azimnagar were in between the medium Hazard Rank (HR2) to low Hazard Rank (HR1) under both the scenarios of embankment overtopping and embankment breaching. People’s perception was almost same as that of model prediction of hazards with little deviation.

They also opined that flood water frequently overtopped the existing crest level of the embankment and flooded the agricultural land areas and fish ghers of Harirampur and caused damage to the standing agriculture crops and fisheries.

Socio-economic aspects, Agriculture crops and Fisheries

These river, canals and beels influence in socio-economic aspects and socio-economic livelihood of people of the area depends on agriculture, fisheries and different bio diversified resources. As the area is the riverine fertile land, over 70% areas are used to cultivate more than one crop. Aman and IRRI are the main crops but during robi season, mustard, onion are cultivated. Jute is also cultivated in a small scale in this area. Fish ghers for culture fisheries found in the areas with well protection by nets.

People's suggestions for river improvements and flood protection

Finally, peoples of that areas recommended that necessary initiatives should be taken as highest priority is to initiate the dredging program in the Ichamati River along with other rivers and Moshakhali khal along with other khals for increasing the conveyance capacity of the river and wetlands to drain out the flood water. On the contrary sufficiently high embankment with sufficient height and width including strong river training works must be implemented.

They also recommended that regular monitoring should be carried out to check the dredging works and improve the quality of river training works and embankment activities. The local administration should be involved in the monitoring works of flood control and dredging activities considering as the urgent requirement. The embankment will provide protection to the area from flood and to save the peoples wealth, crops and fisheries from the hazards caused by floods.

Chapter 8: Conclusions and Recommendations

8.1 Conclusions

The HEC-RAS 1D/2D coupled model successfully applied to determine flood inundation depth and extent in the Harirampur for four different scenarios described earlier considering no flood control embankment, full flood control embankment (17km), overtopping and breaching of flood control embankment at two specific locations (Andharmanik and Gopinathpur). GIS tool was used for development of flood hazard map from model results (inundation depth and extents) for above four scenarios.

Model calibration and verification were performed using 2010 and 2012 time series data for determining optimum Manning's roughness co-efficient for main river and flood plains satisfying criterion a) Hydrographs Visualization; b) Volume fitness and c) Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2).

1D/2D coupled model results were used to develop flood inundation map (extent and depth) for the Model Domain. Floodplains was considered as 2D flow area and the Padma River was considered as 1D flow. Later, the developed model was applied for flood of year 2007 and also for the flood of 100 years return period for preparation of flood inundation maps and flood hazard maps. It was found that 100 years flood inundates more area maximum15% for scenarios two, minimum 6% for scenarios one and almost 10% for scenarios three (overtopping) and scenarios four (breaching) than that of flood of 2007 with the change of inundation in other land type class.

Inundations (both extents and depths) were determined considering the whole areas including at first and analysis was done but in second phase, inundations (both extent and depth) were determined left bank and right bank both including and excluding river areas. The analysis concluded for 2007 flood results were almost similar considering river areas whereas for 100 year flood changes flood free areas for overtopping scenarios and without flood embankment scenarios.

Flood hazard maps with different hazard rank such as very high hazard rank (HR4), high hazard rank (HR3), medium hazard rank (HR2) and less hazard rank (HR1) under four scenarios were prepared from model results. Analysis of different scenarios maps showed that worst situation of hazards was found for scenarios 1 (no flood control measures exists) while the best situation and manageable hazards was found for the scenarios 2 (proposed 17 km full flood control in the left bank of Padma river). Very little changes were found in the flood hazards maps for scenario 3(overtopping) and scenarios 4 (breaching). But hazard ranking of some unions changed from lower rank to higher rank for the flood of 100 years return period in comparison with the hazard rank determined for the flood of 2007.

In case of comparison between 2007 Flood and 100 year Flood for overtopping, hazard rank of the Balla, Gala, Chala and Balara unions would change from HR1 to HR2 while Ramkrisnapur would change from HR3 to HR4. But the union Harukandi would remain same in HR2 whereas for breaching, hazard rank of the Balla, Gala, Chala, Balara and Harukandi unions would change from HR1 to HR2 while Ramkrisnapur would be changed from HR3 to HR4. But the union Gala would remain same in HR2. In every case, the Kanchanpur union was the very high hazard ranked area (HR4) as the most of its boundary goes into the river. This results was checked through consultation to people in the field.

The hazard map could be instrumental for future infrastructural development, natural resources planning and management with necessary protection be identified for implementation to minimize the loss caused by flood flow caused breaching and overtopping the embankment

The flood hazard maps could be further improvised putting various information such as crop damage, erosion prone location, damage of communication infrastructures, plinth level of water point and sanitation, flood vulnerable risk zone identification, homestead and forestry and fisheries damage and many other location specific problems obtained which will be interesting and helpful for different stakeholders.

8.2 Recommendations

The Harirampur is in the most riverine flood prone location along the mighty Padma River. Flood hazard maps were successfully generated from GIS database using the results of HEC-RAS 1D/2D coupled model. Therefore, this model has the potential to replicate in other riverine flood prone areas with improvised knowledge and experiences gained from this study.

Flood inundation and hazard maps are important outputs of the study and can be utilized by flood manager, agricultural farmers, fishers, business man, investors and government official in their routine planning, project development and improved land use planning to save loss through developing awareness of the stakeholders and imparting proper training and participatory dissemination.

Furthermore, this study results can be utilized by the WRM planners in identification of water managements interventions such as river re-excavation, marginal dykes constructions; construction of raised platforms; water bodies capacity improvements; insurances for probable flood damages and flow connectivity establishment for overall improvement of drainage capacity in each water resources system.

Compared to the wide range of researches conducted in other countries, research work carried out in Bangladesh as a riverine country on determination of current hazard status using flood map is not yet up to the mark. As per current state of knowledge, any study using 1D/2D coupled model for managing the Padma River floodplain inundation could not been found implemented yet. This study was conducted using GIS tool in a very simple and straight forward method. The GIS tools is cost effective and adaptive technology for flood hazard mapping, user friendly, interactive may be recommended or macro level planning and assessing preliminary flood protection measures.

The flood inundation maps was prepared with Aster DEM data of 30 m resolutions. Some specific recommendations are given for future improvement of this study:

i. The study was carried out using 1D/2D coupling model. For the comparison purpose and better understanding, pure 2D modeling could be performed in future.

ii. Digital elevation model plays vital role to enhance the capability of model and recommended to use high-resolution digital spatial database for real replication of topography for the better model performance.
iii. For comparison of flood inundation extent between model simulation and real time data, Radarsat images could be used if available which captures ground condition neglecting the cloudy sky.
iv. For hazard mapping, inundation depth and extent have been assigned but other factors i.e. duration of flood, velocity can also be considered for obtaining better result.
v. Community flood risk map can be improvised using hazard information obtained through application of CRA techniques and it can also be compared with Flood Hazard map using modeling approach for future study.

8.3 Limitations of the Study

This is a location specific research along the river Padma, main limitation was data use of minimum numbers of water levels and discharge stations available either in river system or in flood plain of model domain for performing model calibration and validation.

In calibration and validation, the visual observation and volume fits indicates deviation between simulated and observed value only in wet season. Observed hydrograph was found lower than that of simulated hydrograph in both calibration and verification. Probably this was due to not capturing discharge flows in the flood plains during wet season as identified in the model domain. In addition, no contribution of surface runoff from rainfall was considered in this study as its contribution will be less due to small bounding area only in the Harirampur.

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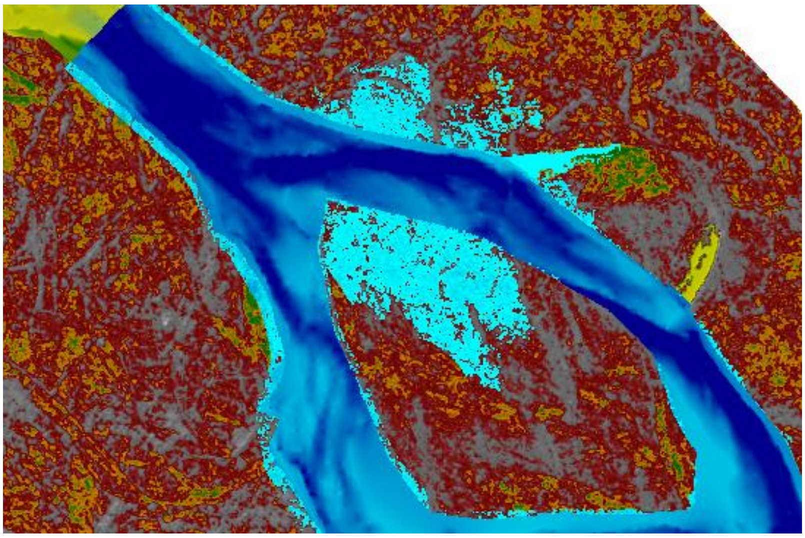
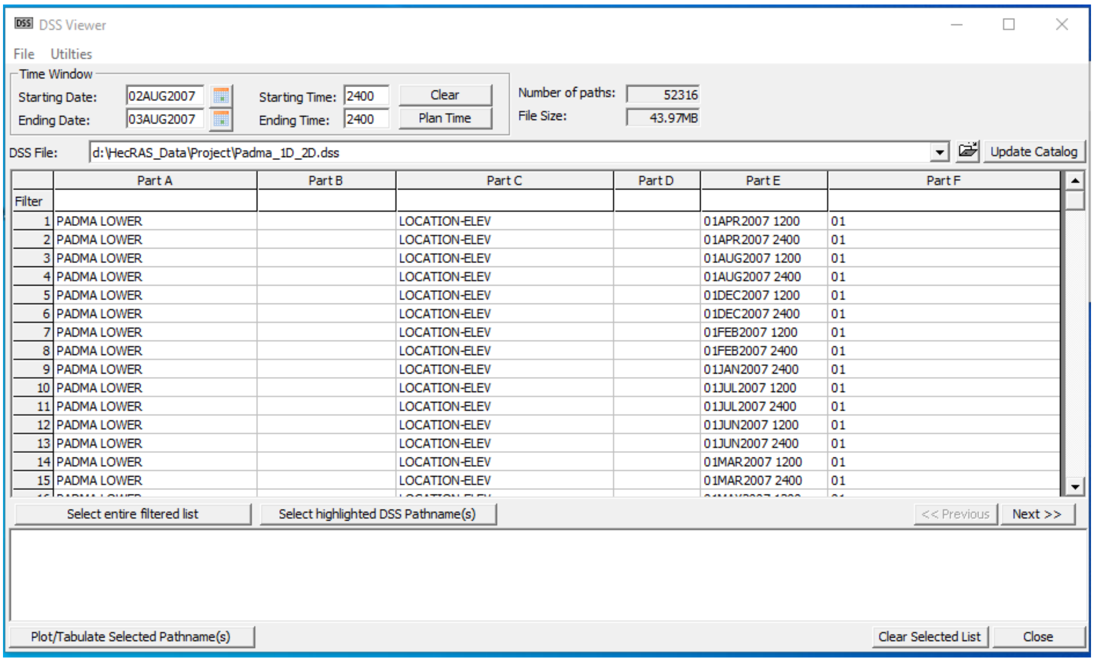
Appendix A
FEATURES OFMODEL

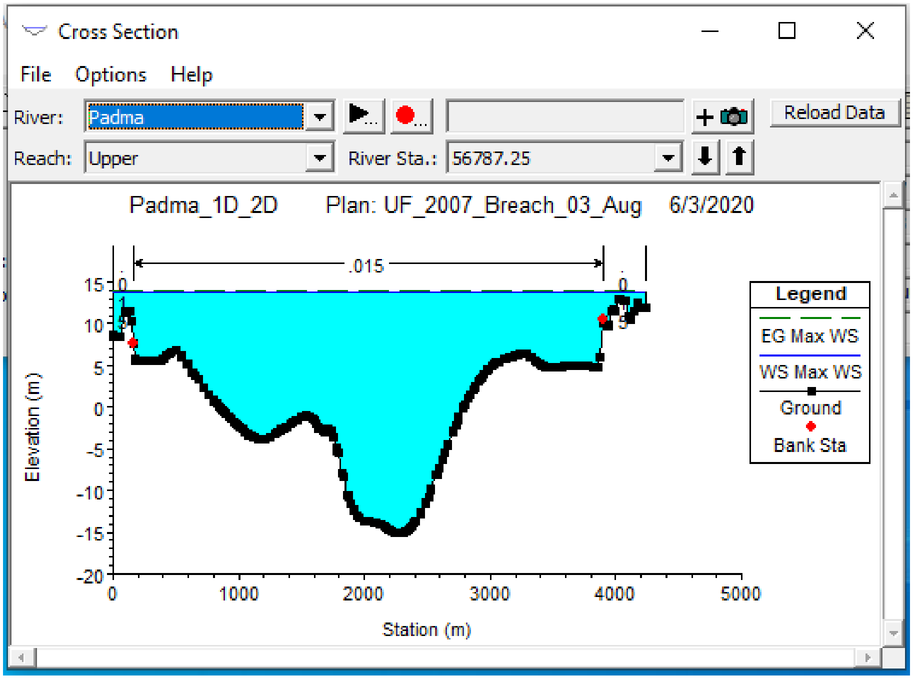
A-1 Unsteady flow simulation in HEC-RAS



A-2 Data storage capability of HEC-RAS



A-3 Graphical and tabular output in HEC-RAS



Profile Output Table - Standard Table 1

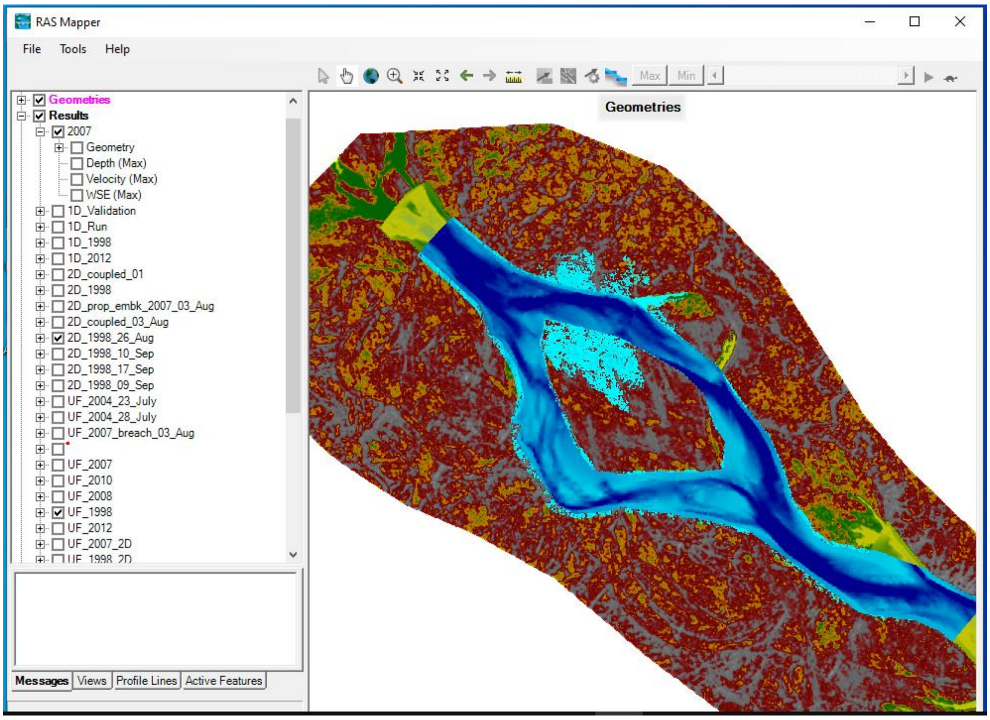
File Options Std. Tables Locations Help

HEC-RAS Plan: UF_2007_breach_03_Aug River: Padma Reach: Upper Profile: Max WS

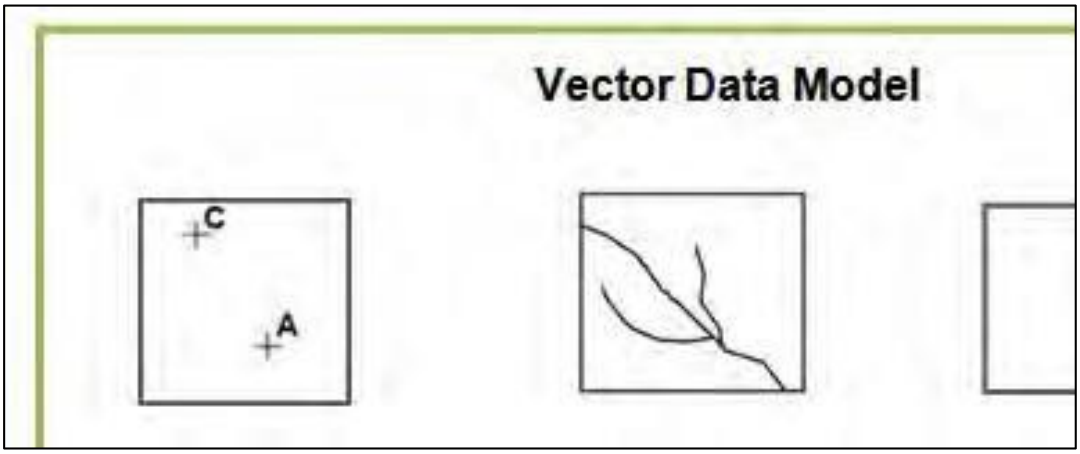
Reach	River Sta	Profile	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude # Chl
Upper	56787.25	Max WS	44286.10	-15.19	13.68		14.01	0.000041	2.57	57033.91	4233.27	0.21
Upper	56620.5*	Max WS	44286.10	-14.92	13.67		14.01	0.000041	2.57	57109.76	4239.80	0.21
Upper	56453.9*	Max WS	44286.10	-14.64	13.67		14.00	0.000041	2.56	57437.28	4246.33	0.21
Upper	56287.25	Max WS	44286.10	-14.37	13.66		13.99	0.000040	2.54	58018.27	4252.86	0.21
Upper	56120.5*	Max WS	44286.10	-15.52	13.66		13.98	0.000039	2.53	58292.38	4259.39	0.21
Upper	55953.9*	Max WS	44286.10	-16.68	13.66		13.97	0.000038	2.50	58800.64	4265.92	0.21
Upper	55787.25	Max WS	44286.10	-17.83	13.66		13.96	0.000036	2.47	59542.04	4272.45	0.20
Upper	55620.5*	Max WS	44286.10	-17.35	13.64		13.96	0.000039	2.51	58501.14	4278.98	0.21
Upper	55453.9*	Max WS	44286.10	-16.86	13.62		13.95	0.000041	2.56	57450.13	4285.52	0.21
Upper	55287.25	Max WS	44286.10	-16.38	13.60		13.94	0.000043	2.60	56390.32	4292.05	0.22
Upper	55120.5*	Max WS	44286.10	-15.45	13.59		13.93	0.000043	2.59	56646.50	4299.54	0.22
Upper	54953.9*	Max WS	44286.10	-14.52	13.59		13.92	0.000042	2.58	56892.29	4307.02	0.22
Upper	54787.25	Max WS	44286.10	-13.59	13.58		13.92	0.000042	2.57	57127.25	4314.51	0.21
Upper	54620.5*	Max WS	44286.10	-14.76	13.58		13.91	0.000040	2.54	57844.91	4309.02	0.21
Upper	54453.9*	Max WS	44286.10	-15.92	13.59		13.90	0.000037	2.48	59089.90	4303.52	0.20
Upper	54287.25	Max WS	44286.10	-17.09	13.59		13.89	0.000033	2.40	60871.75	4257.60	0.19
Upper	54120.5*	Max WS	44286.10	-17.19	13.58		13.88	0.000035	2.43	60263.02	4289.47	0.20

Total flow in cross section.

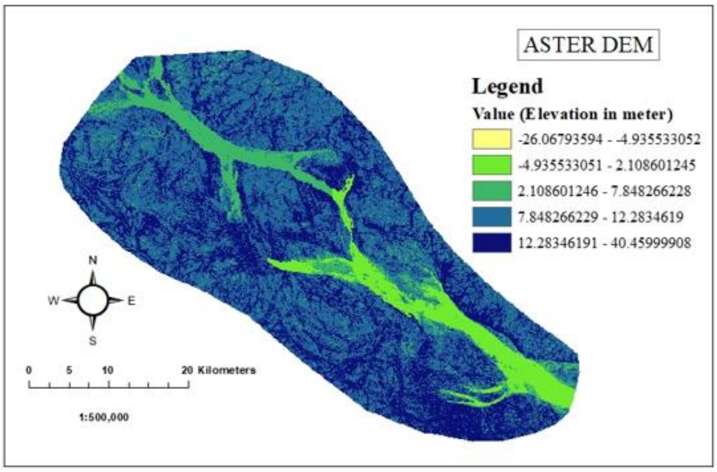
A-4 Inundation mapping of water surface profile in RAS Mapper



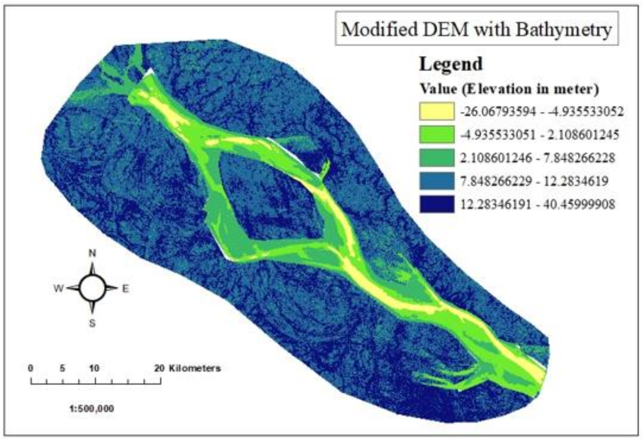
A-5 Representation of vector features



A-6 Raster DEM

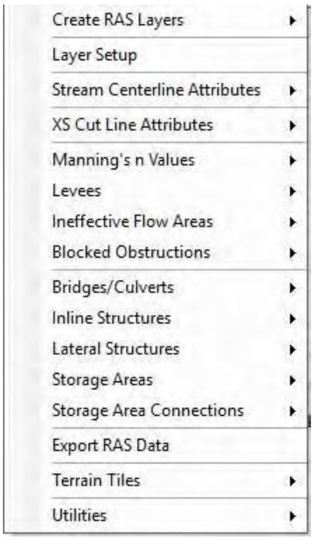


A-7 Representation of TIN land surface

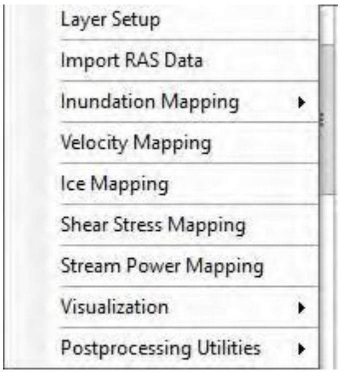


A-8 HEC-GeoRAS toolbar

A-9 HEC-GeoRAS geometry processing menu items



A-10 HEC-GeoRAS mapping menuitems



A-11 Summary of HEC-GeoRAS tools

Tool	Description
	Allows the user to assign *River* and *Reach* names to the stream network.
	Allows the user to assign station values to a stream endpoint.
	Assigns a *LineType* (Left, Channel, Right) value to the Flow Paths feature class.
	Generates cross-sectional cut lines perpendicular to a stream centerline at a specified interval.
	Interactively plots a selected cross section.
	Assigns elevation values to a levee alignment for interpolation.
	Converts HEC-RAS output in SDF format to XML file. Necessary prior to post-processing RAS results.

Appendix B

MORPHOLOGICAL DATA

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1. Cross-Section data of station RMP1 in the Padma River on 28 May 2008

Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	5.025	41	1800	5.15	81	3940	-8.05
2	0	4.5	42	1850	4.9	82	4000	-8.15
3	30	5.07	43	1900	4.95	83	4060	-7.65
4	60	5.14	44	1950	4.8	84	4120	-7.05
5	120	5.1	45	2000	4.8	85	4180	-6.85
6	150	5.11	46	2050	4.88	86	4240	-7.75
7	160	5.4	47	2100	4.9	87	4300	-8.15
8	160	5.52	48	2150	4.95	88	4360	-8.65
9	200	5.22	49	2200	4.92	89	4420	-8.65
10	250	5.25	50	2250	4.8	90	4480	-8.65
11	255	5.3	51	2300	5.11	91	4540	-7.65
12	258	3.37	52	2350	5.19	92	4600	-7.65
13	318	1.37	53	2400	5.12	93	4660	-7.35
14	360	-0.63	54	2450	5.2	94	4720	-7.65
15	420	-3.33	55	2500	5.25	95	4780	-7.65
16	480	-3.43	56	2550	5.12	96	4840	-7.65
17	540	-4.73	57	2600	5.13	97	4900	-8.35
18	600	-6.63	58	2650	5.16	98	4960	-7.95
19	660	-8.93	59	2700	5	99	5020	-7.65
20	720	-10.63	60	2750	4.8	100	5080	-7.65
21	780	-12.63	61	2800	4.9	101	5140	-7.65
22	840	-12.85	62	2810	3.35	102	5200	-8.05
23	900	-12.73	63	2860	1.35	103	5260	-8.45
24	950	-12.63	64	2920	-5.95	104	5320	-8.15
25	1000	-11.63	65	2980	-6.65	105	5380	-8.35

26	1060	-7.63	66	3040	-6.65	106	5440	-8.55
27	1120	-5.63	67	3100	-7.65	107	5500	-8.65
28	1180	-3.63	68	3160	-6.85	108	5560	-8.65
29	1240	-0.63	69	3220	-9.05	109	5620	-8.75
30	1300	0.37	70	3280	-9.65	110	5680	-8.95
31	1360	1.37	71	3340	-9.95	111	5740	-9.65
32	1420	2.37	72	3400	-9.65	112	5800	-10.55
33	1445	3.37	73	3460	-9.65	113	5860	-10.65
34	1450	5.1	74	3520	-8.85	114	5920	-10.55
35	1500	5.15	75	3580	-9.05	115	5980	-10.55
36	1550	4.9	76	3640	-8.65	116	6040	-10.15
37	1600	4.85	77	3700	-8.95	117	6100	-10.05
38	1650	5.11	78	3760	-9.05	118	6160	-9.65
39	1700	5.1	79	3820	-8.95	119	6220	-9.65
40	1750	5.12	80	3880	-8.65	120	6280	-9.65

2. Cross-section data of station RMP 2 in the Padma River on 17 May 2008

Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	4.844	41	1750	4.81	81	3900	4.5
2	0	4.65	42	1800	4.82	82	3950	4.3
3	30	4.7	43	1833	3.09	83	4000	4.25
4	90	4.75	44	1860	2.59	84	4050	4.2
5	90	4.9	45	1920	2.09	85	4100	4.1
6	100	4.7	46	1980	1.59	86	4150	4.11
7	110	4.65	47	2040	1.09	87	4200	4.05
8	150	4.6	48	2100	1.09	88	4210	3.05
9	200	4.55	49	2160	0.59	89	4270	2.05
10	250	4.5	50	2220	0.09	90	4330	1.05
11	300	4.3	51	2280	0.09	91	4390	1.05
12	305	4.2	52	2340	-0.11	92	4450	0.35
13	310	3.07	53	2400	-0.41	93	4510	-0.95
14	370	2.07	54	2460	-0.31	94	4570	-3.35
15	430	1.07	55	2520	-0.51	95	4630	-2.55
16	490	-1.23	56	2580	-0.31	96	4690	0.75
17	550	-2.43	57	2640	-0.41	97	4750	0.65
18	610	-2.63	58	2700	0.09	98	4810	0.05
19	670	-2.73	59	2760	0.59	99	4870	-0.95
20	730	-1.93	60	2820	0.69	100	4930	-3.25
21	790	-1.23	61	2880	0.79	101	4990	-2.95
22	850	-0.93	62	2940	1.09	102	5050	-1.15
23	910	-1.03	63	3000	1.09	103	5110	-1.15
24	970	1.07	64	3060	0.99	104	5170	-0.95
25	1030	2.07	65	3120	1.09	105	5230	-0.95
26	1060	3.07	66	3180	1.59	106	5390	-0.95

27	1070	4.7	67	3240	1.69	107	5450	-1.15
28	1100	4.75	68	3300	2.09	108	5510	-0.95
29	1150	4.8	69	3360	2.59	109	5570	-0.85
30	1200	4.9	70	3420	2.59	110	5630	-0.95
31	1250	4.95	71	3460	3.09	111	5690	-1.05
32	1300	4.9	72	3500	4.1	112	5750	-1.25
33	1350	4.92	73	3550	4.15	113	5810	-1.95
34	1400	4.91	74	3556	4.2	114	5870	-2.15
35	1450	4.92	75	3600	4.25			
36	1500	4.9	76	3650	4.3			
37	1550	4.88	77	3700	4.35			
38	1600	4.85	78	3750	4.4			
39	1650	4.96	79	3800	4.44			
40	1700	4.8	80	3850	4.46			

3. Cross-section data of station RMP 3 in the Padma River on 5 August 2008

Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	4.38	41	1640	-7.3	81	3450	4.16
2	0	4.15	42	1700	-5.3	82	3500	4.35
3	50	3.95	43	1760	-3.7	83	3550	4.3
4	100	4.2	44	1820	-1.3	84	3600	4.25
5	150	4.25	45	1830	0.7	85	3650	4.29
6	166	4.7	46	1840	1.7	86	3700	4.3
7	173	7.24	47	1850	1.7	87	3750	4.33
8	180	7.27	48	1855	2.7	88	3800	4.36
9	189	5.3	49	1860	3.1	89	3850	4.4
10	200	5.1	50	1900	3.2	90	3900	4.5
11	250	5.45	51	1950	3.21	91	3950	4.5
12	273	5.87	52	2000	3.2	92	4000	4.55
13	273	6.234	53	2050	3.25	93	4050	4.5
14	300	5.6	54	2100	3.3	94	4100	4.4
15	350	5.63	55	2150	3.35	95	4150	4.45
16	356	5.39	56	2200	3.2	96	4200	4.55
17	358	6.51	57	2250	3.25	97	4250	4.56
18	366	6.51	58	2300	3.2	98	4300	4.31
19	386	5.31	59	2350	3.3	99	4350	5.1
20	389	2.7	60	2400	3.32	100	4400	5.31
21	440	0.7	61	2450	3.35	101	4450	5.5
22	500	-2.8	62	2500	3.4	102	4500	5.4
23	560	-3.3	63	2550	3.7	103	4550	5.36
24	620	-5.3	64	2600	3.75	104	4600	5.35
25	680	-5.3	65	2650	3.7	105	4650	5.4
26	740	-7.3	66	2700	3.73	106	4700	5.45

27	800	-9.4	67	2750	3.6	107	4750	5.5
28	860	-10.3	68	2800	3.65	108	4800	5.3
29	920	-11.3	69	2850	3.7	109	4850	5.4
30	980	-11.3	70	2900	3.8	110	4900	5.45
31	1040	-12.3	71	2950	3.9	111	4950	5.5
32	1100	-17.3	72	3000	3.95	112	5000	5.36
33	1160	-17.3	73	3050	3.8	113	5050	5.35
34	1220	-25.3	74	3100	3.7	114	5150	5.4
35	1280	-26.3	75	3150	3.9	115	5200	5.36
36	1340	-27.3	76	3200	4	116	5250	5.41
37	1400	-27.3	77	3250	4.1	117	5300	5.42
38	1460	-22.3	78	3300	4.15	118	5350	5.41
39	1520	-17.3	79	3350	4.11	119	5400	5.44
40	1580	-11.3	80	3400	4.14	120	5450	5.45

4. Cross-section data of station RMP4 in the Padma River on 23 April 2008

Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	7.597	41	1243	2.84	81	2720	-0.18
2	0	7.49	42	1260	0.84	82	2780	-1.18
3	23	7.29	43	1280	-5.16	83	2840	-0.88
4	23	7.49	44	1300	-7.16	84	2900	-1.18
5	30	5.15	45	1320	-7.16	85	2960	-1.38
6	39	3.12	46	1340	-5.16	86	3020	-1.48
7	40	2.72	47	1360	-5.16	87	3080	-2.58
8	45	2.62	48	1380	-9.16	88	3140	-2.28
9	50	2.42	49	1400	-9.16	89	3200	-3.18
10	55	2.12	50	1405	-5.16	90	3260	-5.18
11	60	2.12	51	1410	-3.16	91	3320	-5.18
12	65	2.32	52	1418	-1.16	92	3380	-6.18
13	70	2.62	53	1426	2.84	93	3440	-7.18
14	75	2.92	54	1435	4.3	94	3500	-8.28
15	81	3.12	55	1450	4.5	95	3560	-8.78
16	100	6.2	56	1500	4.9	96	3620	-8.88
17	150	6.3	57	1550	5.2	97	3680	-8.98
18	200	6.35	58	1600	5.5	98	3740	-8.88
19	250	6.4	59	1650	5.4	99	3800	-8.98
20	300	6.45	60	1700	5.1	100	3860	-8.88
21	350	6.5	61	1750	4.9	101	3920	-8.98
22	380	6.55	62	1800	4.5	102	3980	-9.08
23	400	6.6	63	1850	4.66	103	4040	-8.88
24	450	6.61	64	1900	4.7	104	4100	-8.78
25	500	6.3	65	1950	4.55	105	4160	-8.88

26	550	6.35	66	2000	4.55	106	4220	-8.78
27	600	6.31	67	2050	4.6	107	4280	-8.83
28	650	6.35	68	2100	4.51	108	4340	-8.88
29	700	6.45	69	2150	4.3	109	4400	-8.88
30	750	6.31	70	2167	2.82	110	4460	-8.78
31	800	6.32	71	2170	0.82	111	4520	-7.18
32	850	6.41	72	2180	0.82	112	4580	-7.18
33	900	6.31	73	2240	0.72	113	4640	-7.58
34	950	6.23	74	2300	-0.18	114	4700	-5.38
35	1000	6.65	75	2360	-0.18	115	4760	-5.58
36	1050	6.5	76	2420	0.22	116	4820	-5.68
37	1100	6.4	77	2480	0.22	117	4880	-3.18
38	1150	5.7	78	2540	-0.88	118	4940	-2.68
39	1200	5.5	79	2600	-0.18	119	5000	-1.18
40	1230	5.2	80	2660	0.72	120	5060	-0.58

5. Cross-section data of station RMP5 in the Padma River on 13 April 2008

Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	5.335	41	1750	6.3	81	3900	-14.98
2	0	5.4	42	1800	6.3	82	3960	-14.98
3	50	5.69	43	1850	6.32	83	4020	-13.98
4	100	5.54	44	1900	6.3	84	4080	-13.38
5	150	5.4	45	1950	6.21	85	4140	-12.98
6	200	5.5	46	2000	6.35	86	4200	-11.98
7	250	5.3	47	2050	6.3	87	4260	-10.98
8	300	5.5	48	2100	6.35	88	4320	-10.58
9	350	5.75	49	2150	6.4	89	4380	-9.98
10	400	5.6	50	2200	6.5	90	4440	-8.98

11	450	5.5	51	2250	6.51	91	4500	-8.08
12	500	5.4	52	2300	6.71	92	4560	-8.18
13	550	5.2	53	2350	6.8	93	4620	-6.98
14	573	6.86	54	2400	6.6	94	4680	-5.98
15	579	9.35	55	2450	6.45	95	4740	-4.98
16	587	9.32	56	2500	6.5	96	4800	-3.98
17	t597	5.91	57	2550	6.55	97	4860	-3.68
18	600	5.6	58	2600	6.35	98	4920	-3.08
19	650	5.11	59	2650	6.11	99	4980	-3.03
20	700	6.12	60	2700	6.15	100	5040	-1.18
21	750	6.15	61	2750	5.45	101	5100	0.02
22	800	6.5	62	2765	3.02	102	5160	1.02
23	850	6.4	63	2825	2.02	103	5220	1.82
24	900	6.45	64	2880	1.02	104	5280	2.32
25	950	6.4	65	2940	-3.08	105	5340	2.52
26	1000	6.2	66	3000	-5.98	106	5358	3.02
27	1050	6.21	67	3060	-8.68	107	5375	6.6
28	1100	6.3	68	3120	-8.98	108	5400	6.7
29	1150	6.4	69	3180	-10.88	109	5450	6.55
30	1200	6.41	70	3240	-12.78	110	5500	6.3
31	1250	6.42	71	3300	-12.98	111	5550	6.1
32	1300	6.45	72	3360	-14.28	112	5600	6
33	1350	6.5	73	3420	-14.58	113	5660	5.9
34	1400	6.5	74	3480	-15.18	114	5700	5.95
35	1450	6.6	75	3540	-15.28	115	5750	5.9
36	1500	6.7	76	3600	-15.38	116	5800	5.8
37	1550	6.7	77	3660	-15.98	117	5850	5.5
38	1600	6.71	78	3720	-15.18	118	5900	5.4
39	1650	6.5	79	3780	-15.08	119	5950	5.45

40	1700	6.65	80	3840	-15.28	120	6000	5.35

6. Cross-section data of station RMP6 in the Padma River on 27 April 2008

Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	8.475	41	1936	5.8	81	4253	0.22
2	0	8.1	42	1996	5.75	82	4313	0.72
3	30	8.05	43	2056	5.7	83	4373	0.82
4	37	8.42	44	2116	5.5	84	4433	-4.88
5	40	6.4	45	2176	5.45	85	4493	-6.78
6	47	2.15	46	2236	5.3	86	4553	-7.78
7	69	2.11	47	2296	5.25	87	4613	-8.78
8	80	5.2	48	2356	5.2	88	4673	-10.78
9	140	5.15	49	2416	4.7	89	4733	-8.78
10	200	5.1	50	2450	4.25	90	4793	-10.68
11	260	5.14	51	2453	3.22	91	4853	-10.78
12	320	5.17	52	2513	1.22	92	4913	-12.78
13	380	5.1	53	2573	2.72	93	4973	-12.78
14	440	4	54	2633	1.12	94	5033	-11.88
15	500	4.1	55	2693	0.82	95	5093	-11.78
16	536	4.11	56	2753	0.12	96	5153	-12.78
17	596	3.5	57	2813	-0.58	97	5213	-12.78
18	656	3.4	58	2873	-0.58	98	5273	-12.68
19	676	3.6	59	2933	1.22	99	5333	-12.78
20	701	3.49	60	2993	1.42	100	5393	-11.78
21	736	4.7	61	3053	1.22	101	5453	-11.78
22	796	5.92	62	3113	1.07	102	5513	-11.78
23	856	5.75	63	3173	-0.68	103	5573	-12.68
24	916	5.8	64	3233	-1.78	104	5633	-12.58

25	976	5.9	65	3293	-1.68	105	5693	-10.88
26	1036	6.1	66	3353	-0.78	106	5753	-10.98
27	1096	6.15	67	3413	0.02	107	5813	-8.78
28	1156	6.2	68	3473	1.12	108	5873	-6.78
29	1216	6.25	69	3533	1.22	109	5933	-4.68
30	1276	6.21	70	3593	1.22	110	5993	-0.68
31	1336	6.22	71	3653	1.22	111	6053	1.22
32	1396	6.27	72	3713	2.22	112	6113	1.52
33	1456	6.3	73	3773	2.72	113	6173	1.82
34	1516	6.33	74	3833	2.82	114	6230	3.22
35	1576	6.12	75	3893	2.92	115	6290	5.1
36	1636	6.15	76	3953	2.82	116	6320	5.4
37	1696	6.11	77	4013	1.22	117	6380	5.6
38	1756	6.15	78	4073	1.12	118	6440	5.5
39	1816	6.1	79	4133	0.12	119	6500	5.7
40	1876	5.9	80	4193	-0.28	120	6560	6.1

7. Cross-section data of station RMP7 in the Padma River on 17 April 2008

Sl. No.	Distance (m)	RL(m)	Sl. No.	Distance(m)	RL(m)	Sl. No.	Distance(m)	RL(m)
1	0	8.178	41	2219	-5.08	81	4560	5.25
2	0	7.978	42	2279	-5.68	82	4620	5.3
3	30	8.12	43	2339	-6.58	83	4680	5.29
4	90	8.2	44	2399	-7.98	84	4740	5.27
5	150	8.18	45	2459	-8.58	85	4800	5.25
6	210	8.19	46	2519	-8.58	86	4860	5.5
7	270	8.12	47	2579	-6.58	87	4920	5.8
8	330	8.05	48	2639	-4.98	88	4980	6.1
9	390	7.1	49	2699	-4.48	89	5040	6.3
10	419	6.3	50	2759	-2.68	90	5100	6.5
11	448	3.42	51	2819	-0.78	91	5160	6.7
12	479	1.42	52	2879	-0.88	92	5220	6.9
13	539	-0.78	53	2939	-0.78	93	5380	7.1
14	599	-4.48	54	2999	-2.08	94	5440	7.15
15	659	-3.58	55	3059	-0.78	95	5500	7.2
16	719	-3.58	56	3119	-0.48	96	5560	7.25
17	779	-3.28	57	3179	-0.38	97	5620	7.3
18	839	-2.88	58	3239	0.82	98	5680	7.35
19	899	-2.58	59	3299	1.72	99	5740	7.4
20	959	-0.68	60	3320	3.42	100	5800	7.45
21	1019	-0.48	61	3380	4.95	101	5860	7.5
22	1079	-0.48	62	3420	5.1	102	5920	7.55
23	1139	-0.78	63	3480	5.05	103	5980	7.56
24	1199	-2.58	64	3540	4.7	104	6040	7.6

25	1259	-3.58	65	3600	4.95	105	6100	7.65
26	1319	-4.58	66	3660	5.06	106	6160	7.6
27	1379	-1.58	67	3720	5.1	107	6220	7.55
28	1439	-1.58	68	3780	5.12	108	6280	7.6
29	1499	-0.58	69	3840	5.14	109	6340	7.7
30	1559	-0.28	70	3900	5.16	110	6400	7.8
31	1619	0.82	71	3960	5.18	111	6460	8.05
32	1679	1.52	72	4020	5.2	112	6520	8.1
33	1739	1.72	73	4080	5.21	113	6580	8.11
34	1799	2.92	74	4140	5.15	114	6640	8.12
35	1859	3.12	75	4200	5.19	115	6700	8.15
36	1919	-2.48	76	4260	5.22	116	6760	8.2
37	1979	-2.53	77	4320	5.1	117	6820	8.25
38	2039	-2.68	78	4380	5.15	118	6880	8.2
39	2099	-3.88	79	4440	5.19	119	6940	8.25
40	2159	-4.78	80	4500	5.22	120	7000	8.3

8. Cross-section data of station RMP8 in the Padma River on 04 August 2008

Sl. No.	Distance	RL	Sl. No.	Distance	RL	Sl. No.	Distance	RL
1	0	9.432	21	637	1.34	40	1777	-2.86
2	0	9.23	22	697	2.64	41	1837	1.54
3	60	9.44	23	757	-0.36	42	1897	2.89
4	120	9.35	24	817	-0.16	43	1927	3.64
5	171	9.57	25	877	-0.06	44	1950	4.97
6	171	9.9	26	937	-0.86	45	2010	5.02
7	173	9.9	27	997	0.24	46	2070	5.1
8	219	10.088	28	1057	-0.36	47	2130	5.11

9	219	10.31	29	1117	-1.11	48	2190	5.15
10	252	10.1	30	1177	-1.06	49	2250	5.2
11	265	9.3	31	1237	-0.86	50	2310	5.21
13	272	9.4	32	1297	-1.06	51	2370	5.18
14	276	6.1	33	1357	-0.36	52	2430	5.22
15	277	3.64	34	1417	-0.26	53	2490	5.11
16	337	2.64	35	1477	-2.36	54	2550	5.15
17	397	1.94	36	1537	-4.36	55	2560	5.14
18	457	1.64	37	1597	-4.46	56	2620	5.12
19	517	-0.46	38	1657	-4.41	57	2680	5.16
20	577	-0.86	39	1717	-4.36	58	2740	5.19