FLOOD INUNDATION MAPPING AND FLOOD MITIGATION OF GHAGHAT RIVER FLOODPLAIN USING HEC-RAS 1D/2D COUPLED MODEL

M. Sc. Engineering Thesis

by

Farjana Akter

DEPARTMENT OF WATER RESOURCES ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

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A Thesis Submitted

by

Farjana Akter
(Roll No. 1015162022P)

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CERTIFICATION OF APPROVAL

The thesis titled "Flood Inundation Mapping and Flood Mitigation of Ghaghat River Floodplain Using HEC-RAS 1D/2D Coupled Model", submitted by Farjana Akter, Student ID. 1015162022 P, Session October 2015, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of **Master of Science in Water Resources Engineering** on **30th May, 2022.**

Mostafa

.... **Chairman (Supervisor)**

Dr. Md. Mostafa Ali
Professor
WRE, BUET, Dhaka

.... **Member (Ex- Officio)**

Dr. A T M Hasan Zobeyer
Professor and Head
WRE, BUET, Dhaka

....Yunus.............. **Member**

Dr. Anika Yunus
Professor
WRE, BUET, Dhaka

.... **Member**

Dr. Badal Mahalder
Assistant Professor
WRE, BUET, Dhaka

Md Asad Hussain

.... **Member (External)**

Dr. Mohammad Asad Hussain
Professor
IWFM, BUET, Dhaka.

CANDIDATE'S DECLARATION

This is to certify that this M.Sc. thesis entitled **"Flood Inundation Mapping and Flood Mitigation of Ghaghat River Floodplain Using HEC-RAS 1D/2D Coupled Model"** has been done by me under the supervision of Dr. Md. Mostafa Ali, Professor, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka. I do hereby declare that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma from any other institution.

30th May, 2022

Farjana Akter

Farjana Akter

Roll No. 1015162022 P

Session: October 2015

Dedicated to

Dedicated to the memory of Dr. Umme Kulsum Navera

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Z	Elevation of the main channel inverts
Y	Depth of water at cross sections
V	Average velocities (total discharge/ total flow area)
A	Velocity weighting coefficients
G	Acceleration due to gravity (m s^{-2})
h_e	Energy head loss
L	Discharge weighted reach length
S_f	Representative friction slope
C	Expansion or contraction loss coefficient
L_{lob}, L_{ch}, L_{rob}	*X*-section reach length specified for flow in the left overbank, main channel and right overbank respectively
P	Hydrologic pressure force
W_x	Force due to the weight of water
F_x	Force due to external friction losses
P	Density of water
ΔV_x	Change on velocity
Γ	Unit weight of water
A_i	Wetted area of the cross section
S_0	Slope of the channel, based on mean bed elevations
z_i	Mean bed elevation
T	Shear stress
$\bar{P}$	Average wetted perimeter
$\bar{R}$	Average hydraulic radius (r=a/p)
B	Momentum coefficient that accounts for a varying velocity distribution in irregular channels
$\bar{S}_f$	Slope of the energy grade line (friction slope)
Z	Surface elevation (m)
N	Manning resistance
F	Coriolis (s^{-1})

LIST OF ABBREVIATION

1D/2D	One dimensional/Two Dimensional
ArcGIS	Arc Geographic Information System
BTM	Bangladesh Transverse Mercator
BWDB	Bangladesh Water Development Board
DEM	Digital Elevation Model
DL	Danger Level
DTM	Digital Terrain Model
FCDI	Flood Control, Drainage and Irrigation
FFWC	Flood Forecasting and Warning Centre
FPA	Flood Prone Area
GBM	Ganges-Brahmaputra-Meghna
GIP	Gaibandha Improvement Project
GIS	Geographic Information System
GLE	Ghaghat Left Embankment
GUI	Graphical User Interface
HEC-RAS	Hydrologic Engineering Center River Analysis System
NASA	National Aeronautics and Space Administration
NSE	Nash-Sutcliffe efficiency
NWMP	National Water Management Plan
SRTM	Shuttle Radar Topographic Mission
TIN	Triangular Irregular Networks
USGS	United State Geological Survey
WL	Water Level

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ABSTRACT

Ghaghat River flows through North West region of Bangladesh in Nilphamari, Rangpur and Gaibandha district. It is a distributary of Teesta River which originates at Jaldhaka in Nilphamari district. It carries flow from Teesta to Brahmaputra River thus it has a major influence during flood period. During monsoon, when water level of Ghaghat River at Gaibandha crossed the danger level, the floodplain of this river is inundated. At almost every year people of Gaibandha municipality experienced high magnitude flood which is the most devastating natural hazard of this region. The aim of this study is to develop a Hydrodynamic model for Ghaghat River basin area using HEC-RAS 1D/2D coupled model to prepare flood inundation mapping. Flood inundation mapping of Ghaghat River has been carried out to identify the flood affected area for this river basin. A HEC-RAS 1D model of Ghaghat River has been set up using bathymetry of 2013 and the discharge and water level hydrographs in upstream and downstream boundaries respectively. A HEC-RAS 1D/2D coupled model of Ghaghat river basin has been set up for the same condition for flood mapping. HEC-RAS 1D model has been calibrated for 2013 (June to November) for the water level data at Gaibandha and validated for the period of 2015 (June to November) for same condition. Finally, a 1D-2D coupled model of Ghaghat River floodplain has been set up in HEC-RAS. This coupled model is calibrated and validated for Manning's roughness coefficient ‘n’ = 0.020 for the year of 2013 and 2015 respectively. The values of R^2 and NSE have been found 0.9596 and 0.956 for calibration and 0.9027 and 0.730 for validation respectively. The qualitative comparison has been done among FFWC observed map, satellite image and simulated model. After calibration and validation of the 1D-2D coupled model, it has been simulated for the historical flood events of 2004, 2007, 2011, 2012 and 2017. The study area (total 1532 km^2) consist of three districts where Nilphamari, Rangpur and Gaibandha covered 13.81 km^2, 951.75 km^2 and 566.42 km^2 respectively.

This study proposed three scenarios for mitigating floods in the study area. The first scenario involved extending and increasing the height of the left and right embankments of the Ghaghat River from downstream. The second scenario involved dredging the cross-sections at the downstream and nearest one-third length of the river. The third scenario involved extending and raising the height of the embankment along with dredging the cross-section at the nearest one-third length of Ghaghat River. Approximately 19.27% area of the floodplain of the Ghaghat River has been affected by flooding for 2004. From all the flood mitigation scenarios on the basis of cost estimation and reduced percentage of flood mitigation, scenarios 3.2 has been suggested (raising the existing embankment height by 1 meter up to 20 kilometers from downstream at left bank and right bank and raising the existing embankment height by 1.2 meter from 20 kilometers to 37 kilometers from downstream at left bank and from 20 kilometers to 27.5 kilometers at right bank and construction of new embankment of 1.2m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and dredging 1.0 meter for cross-sections 15 to 22 (49.5-73 kilometers)).

CHAPTER 1
INTRODUCTION

1.1 Background and Present State of the Problem

Bangladesh, owing to its position on the global map in the South-Asian region, is one of the most flood affected country (Shrestha, 2008). Bangladesh almost entirely situated on flat low land that is barely above sea level (Saleemul et. al, 2008). It consists mainly of regions relating to or situated on a river or riverbank (such delta plains occupy almost 80% of the country. Furthermore, the Bengal Delta is the largest delta in the world) (Rahman, 2002). Bangladesh’s climate, similar to other South Asian countries, is heavily affected by monsoons (which are seasonal prevailing winds that bring rain between May and September and detract precipitation between October and April). As a result, precipitation occurs seasonally, with extreme amount of rains in high and low range (Shahid, 2010).

Ghaghat River (192 km long) flows through North West region of Bangladesh in Nilphamari, Rangpur and Gaibandha district. This river is a distributary of Teesta River, originated at Jaldhaka in Nilphamari district and after passing through Gaibandha town (few km norths of Fulchhari Ghat) joins to the Brahmaputra river (BWDB, 2011). In the northern part of Bangladesh, Ghaghat River is an important inland open water-body. Its co-ordinates are 25°19'0" N and 89°37'60" E. Ghaghat River flow varies from 1 to 241m^3/sec (Rashid, et. al, 2015). It carries flow from Teesta to Brahmaputra River thus it has a major influence during flood period. During monsoon, when water level of Ghaghat River at Gaibandha crosses the Danger Level (21.70 mPWD), the floodplain of this river has been inundated. At 1988, 1998, 2004, 2008, 2009, 2011-2015, 2017 and 2019 people of Gaibandha municipality experienced high magnitude flood which is the most devastating natural hazard of this region. The people of this floodplain area had experienced a profound impact on their living.

In 2019, due to excessive upstream flow of Ghaghat, eighteen points of flood control embankment was damaged and around 0.4 million people of Gaibandha was flooded. To determine the flood-affected region for this river basin, flood inundation mapping for the Ghaghat River needs to be done.

Yearly flooding during monsoon season and other forms of rainy weather has continued to force low-lying populations (many of which are in poverty) to adjust their lifestyle in order to prepare for the worst. For example, some villages attempt to avoid the effects of the flooding by building above the typical water level a flood can reach. After flooding, the presence of floodwater also poses a risk, as overflowing water can contain waterborne diseases which may spread to those displaced by flooding.

Due to monsoon flood Ghaghat River and its floodplain have been inundated almost every year which showed in figure 1.1.

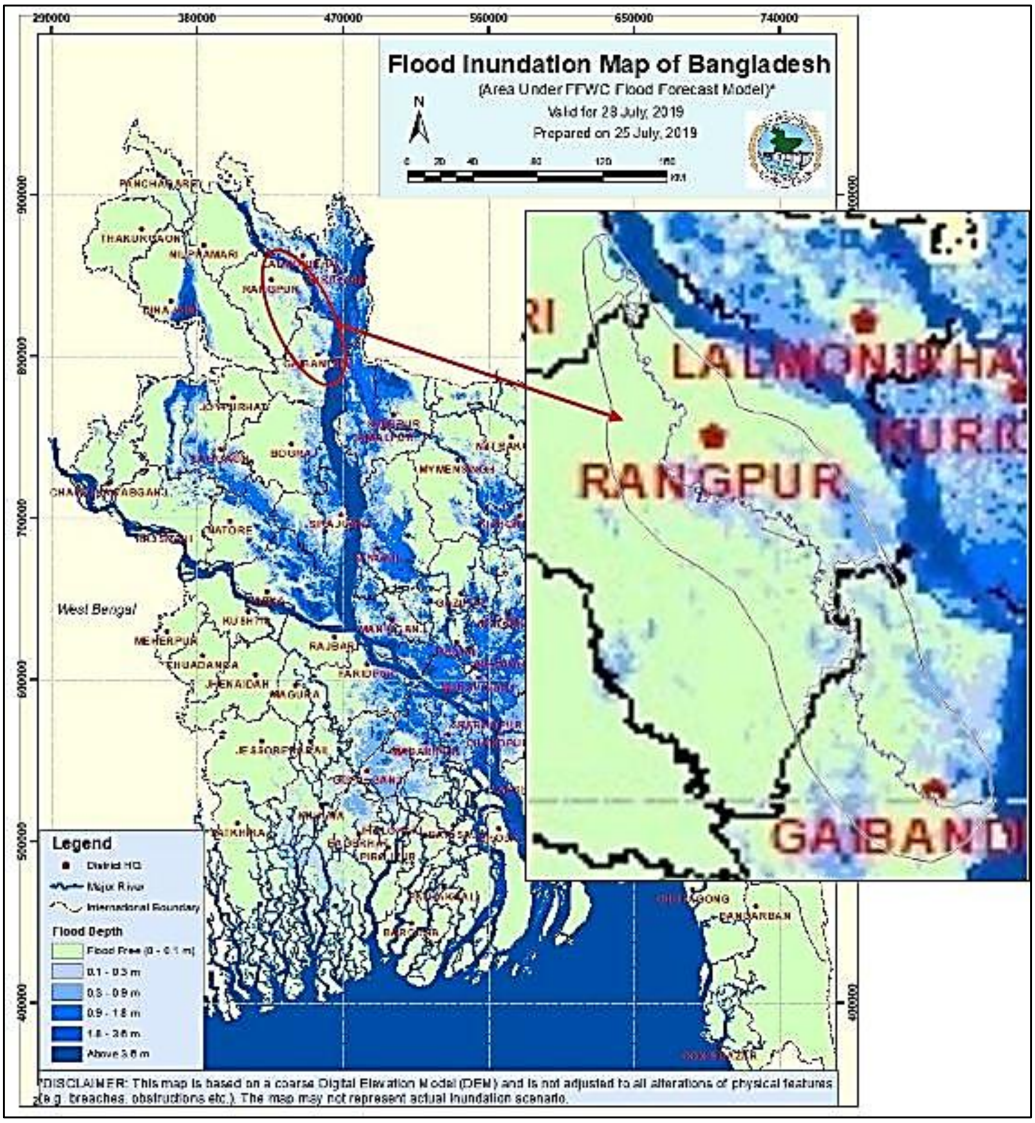

Figure 1.1: Flood inundation map of Bangladesh (Source: FFWC)

Hence the difficulties of people increase of the region in various ways. It has been essential to minimize the difficulties of people due to flood in this area.

Flood occurred in this region due to various reasons. Drainage problem in Ghaghat River are excessive due to floodwater from Teesta and Ghaghat against the capacities of existing regulators, insufficient discharge capacity of the existing regulators/sluices due to influx of excessive rainfall runoff into the drainage basin through inter linked canal or natural channels, localized drainage congestion along the existing embankments due to lack of facilities which leads to public-cut of the flood embankment.

Figure 1.2: Major river floodplains of Bangladesh (Alam et al., 1990)

A number of studies have also been done for the major rivers and floodplains of Bangladesh shown in figure 1.2 (Tingsanchali & Karim, 2005; Nishat, 2017; Ali, et al., 2018, Alam et al., 1990). However, flood inundation of Ghaghat River has not been studied yet, let alone mitigation of flood in this area. There are many commercial models and open source mathematical models for hydrodynamic assessments. However, open source software HEC-RAS (Hydrologic Engineering Center River's Analysis System) has been chosen to carry out this study due to its accuracy in analysis of river system and special feature of 1D-2D river-floodplain coupling simulation (HEC-RAS, 2016).

In this context, an approach has been developed in this study to establish a hydro-dynamic model for the Ghaghat River which has been selected as the study area. HEC-RAS, version 5.0.1 (HEC-RAS, 2016) is a useful tool for developing a hydro-dynamic model for Ghaghat River.

1.2 Scope of the Research Work

The Ghaghat River Basin is one of the most flood prone areas in Bangladesh. Presently the upstream of the Ghaghat is connected with the Teesta through breaches over a length about 7 Km, which was formed by the flood in 1988. Therefore, flood water and large quantities of sediment conveyed by the Teesta easily enter the Ghaghat. Besides the excess flood water from the Teesta is retarded in the upstream reaches and sediment is deposited in the upstream riverbed and floodplain.

The scope of the research study has been assessing the Ghaghat River Floodplain for the preparation and comparison of flood inundation map of Ghaghat River Floodplains as well as mitigation of flood (by embankment, dredging, and combination of embankment & dredging). For this purpose, a hydrodynamic model has developed by HEC-RAS and calibrated and validated the model for Ghaghat River Floodplain. This study has focused not only on the preparation of Flood inundation mapping. The model has been also calibrated and validated and then developed best possible solution to mitigate flood based on different options.

1.3 Objective of the Study

1. A Calibrated and validated HEC-RAS 1D/2D coupled model of Ghaghat River will be developed to prepare flood inundation map.
2. Qualitative comparison between developed flood inundation map with the observed flood map (BWDB & USGS) for different year.
3. To compare different flood mitigation options (embankment, dredging and link canal) for Ghaghat River to establish a flood mitigation plan.

Possible Outcomes

1. A Calibrated and validated hydrodynamic model of the Ghaghat River has been found after the study.
2. Monsoon flood inundation map of the Ghaghat River floodplain which can identified the inundated area to minimize the damage from flood.
3. Applicability of the HEC-RAS 1D/2D coupled model in modeling flood inundation to the floodplain which can be a basis for application to other floodplains having similar characteristics.

1.4 Organization of the Thesis

The thesis contains seven chapters. The organization of the chapters is as follows:

Chapter 1 is an introduction to the thesis. Here, the background and present state of the study area and objective of the thesis have been discussed.

Chapter 2 is literature review. This chapter contains review of literature on several topics which include-review of previous studies for flood inundation mapping of different River, flood mitigation option of different River has been described. Mainly focuses on the reviews of literature related to the objectives and outcomes of this study. Findings of the previous research works related to this study have also been summarized in this chapter.

Chapter 3 is theoretical background. This chapter contains the basic concepts and theories of different hydrodynamic processes in HEC-RAS and also deals with the basic theory and equations behind the model study.

Chapter 4 is methodology. This chapter contains the steps followed in the present thesis to setup, from data collection to calibration/validation of models and assess flood inundation mapping of Ghaghat River.

Chapter 5 is data analysis and model setup. This chapter represents the preprocessing of data for model setup. The hydrodynamic model HEC-RAS selected for this study operates on computational time step and uses digital elevation data, water level, morphological data and river discharge.

Chapter 6 is results and discussions which describes the detail procedure followed to setup model of Ghaghat River and also describes the parameters used to calibrate the model and evaluate the performance of calibration/validation. This chapter also gives the selection of different flood mitigation option to decrease the flood of Ghaghat River.

Chapter 7 is conclusions and recommendations. This chapter gives a summary of the results obtained in this study and also includes recommendations for further study relevant to this topic.

CHAPTER 2
LITERATURE REVIEW

2.1 General

This chapter provides a brief literature review of Ghaghat River, flood inundation, flood mitigation scenarios and hydro-dynamic model. Doing a careful and thorough literature review is essential for research at any level. It is basic homework that is assumed to have been done vigilantly, and a given fact in all research papers. It's not only surveys what research has been done in the past on this topic, but it also appraises, encapsulates, compares and contrasts, and correlates various scholarly books, research articles, and other relevant sources that are directly related to this research. The available study reports, project documents, published scientific articles have collected and reviewed to get information on the study area and corresponding water resources related to this study. Some of the important and selected previous studies have briefly described in this chapter around the world and in Bangladesh.

2.2 Previous Studies and Research on Flood Inundation

A number of studies have been carried out in the past, particularly concerning the floodplain inundation mapping, flood hazard mapping, flood forecasting and others nonstructural measures. Some of these researches have been summarized in order to gain proper conception about flooding problem and mitigation managements and to be able to prepare a good quality floodplain inundation map.

2.2.1 Flood Inundation Related Studies around the World

Duvvuri and Narasimhan (2013) studied flood inundation mapping of Thamiraparani river basin using HEC-GeoRAS and SWAT model. The study had carried out flood frequency analysis for the flow values obtained from SWAT to calculate the flow magnitudes of several recurrence intervals (2, 5, 10, 25, 50 and 100 year) using a statistical technique known as the Log-Pearson type-III distribution. Author prepared flood map for the 2, 5, 10, 25, 50 and 100 years return period and observed flood depth and extent continuously increase with frequency interval. Author also studied the impact of levees on flood extent and inundation depth.

Abera (2011) studied flood mapping and modeling on Fogera flood plain. HEC-HMS, HEC-RAS and HEC-GeoRAS were used in river basin flood modeling. Author found a flow value of 91.8, 202.4, 273.1, and 308.4 m^3/sec for return periods of 2, 10, 50 and 100 respectively by hydrologic model HEC-HMS. This flow value was used to generate water surface profile for flood inundation mapping by hydraulic model HEC-RAS. The flooded area for the return periods 2, 10, 50 and 100 years was 12.63, 18.63, 21.31 and 22.5 km^2 respectively. He found most of the area flood depth is less than 1.5 m. Author also found 88% of agricultural land, 11.6% of agro-pastoral land and 1.36% river inundated by the flood.

Pathak (2016) studied on modeling of floodplain inundation for Monument Creek, Colorado. In their study, flood plain map was created for 11.4 km reach of monument creek at Colorado Springs, Colorado. The study presented the approach for terrain modeling and flood plain mapping. It incorporated the hydraulic modeling using HECRAS and terrain modeling using Arc Hydro to create floodplain map. The reach of Colorado Spring was successfully modeled and map was delineated showing the flooded areas along the Monument creek. Change was noticed between the topography of the flood plain and digital elevation model, which could be because of not containing high-resolution terrain data. It was found that high-resolution digital data of the geometry of river are hence required to create an effective terrain models as the accuracy of hydrologic modeling largely depends upon the accuracy of terrain data used in GIS. In the city the most drainage structures are designed for 100-year flood level, and as such the structures, if exposed to higher magnitude flood level, were to get affected by flood waters.

Chow (1988) presented a straightforward 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 that GIS is an effective environment for floodplain mapping and analysis.

Kalra and Ahmad (2012) studied two-dimensional flow routing capabilities of hydrologic engineering center's river analysis system (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 digital elevation model of 1/9-arc second resolution was used to generate the two-dimensional (2D) flow area and flow geometrics. Stream flow data available from gauging station USGS08114000 were used for the full unsteady flow hydraulic modeling 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.

Shafwat (2022) described that river renaturation can be an effective management method for restoring a floodplain's natural capacity and minimizing the effects during high flow periods. A 1D-2D Hydrologic Engineering Center–River Analysis System (HEC-RAS) model, in which the flood plain was considered as 2D and the main channel as 1D, was used to simulate flooding in the restored reach of the Spree River, Germany. When computing in this model, finite volume and finite difference approximations using the Preissmann approach are used for the 1D and 2D models, respectively. To comprehend the sensitivity of the parameters and model, several scenarios were simulated using different time steps and grid sizes. Additionally, dykes, dredging, and changes to the vegetation pattern were used to simulate flood mitigation measures. The model predicted that flooding would occur mostly in the downstream portion of the channel in the majority of the scenarios without mitigation measures, whereas with mitigation measures, flooding in the floodplain would be greatly reduced. By preserving the natural balance on the channel's floodplain, the restored area needs to be kept in good condition. This renaturation project was one of the largest river renovations in the state of Brandenburg. The extent of the renaturation was over a length of 11 km and an area of 400 ha. Different mitigation measures adopted in the model provided a change in the inundation pattern. As the results show above, all the measures like change in vegetation pattern (Manning's n), dredging, and dyke inclusion in the model reduced the flood inundation significantly.

This suggests that the use of such measures could be important to protect the surrounding areas, which hold economic value due to their touristic appeal. Therefore, mitigating measures that balance the area's economic and environmental aspects must be considered in light of the potential for floods.

2.2.2 Flood Inundation Related Studies in Bangladesh

Khan (2009) studied flood inundation mapping of Kaliganga-Dhaleswari river basin. In his study, an application of HEC-RAS and HEC-GeoRAS model ware applied in the Kaliganga-Dhaleswari floodplain. He used discharge and water level data in 2004. He prepared floodplain map and the area of inundation within the floodplain during the post monsoon. He found the downstream area of the basin is more vulnerable to flooding then the upstream area. The area of inundation found from the flood map is about 3 to 4 km on both bank of the river. He showed different thanas like Dhamrai, Savar and Saturia were inundated by 11.81, 9.0 and 47.38% of the total area respectively. He also showed the inundation depth of different thanas. Maximum and minimum inundation depth was 4.7m in Savar thana and 0.3 m in Manikganj Sadar respectively. The calibration and validation of hydrodynamic model and floodplain inundation was absent in his study.

Islam (2010) studied flood inundation map of Bangladesh using MODIS time-series images. They detected the spatio-temporal extent of inundation resulting from the floods in 2004 and 2007 in Bangladesh using time-series MODIS surface reflectance data. They compared inundation map which was developed using MODIS data with a corresponding RADAR-SAT image, where both images refer to the satellite-based remote-sensing data. MODIS has advantages over microwave satellite because it has a high observational frequency.

Rouf (2015) worked on flood inundation map in a low-lying riverine flood prone area of Bangladesh at Sirajgonj district. In her study, weather forecast model coupled with a hydrologic model and resulted hydrodynamic model for predicting floods in Jamuna River at Sirajgonj district were used. Weather Research and Forecasting model (WRF3.0) was used to predict rainfall over the basin with lead-time of 6 days in her study. At first hydrological model HEC-HMS 4.0 (Hydrologic Engineering Center – Hydrologic Modeling System) was calibrated and validated with discharge at Bahdurabad station which was derived from Global Weather Rainfall Data with Clark's Unit Hydrograph transformation method. Output from the WRF model with hydrologic model HEC-HMS was then coupled. 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 (Hydrologic Engineering Center-River Analysis System) hydrodynamic model were ingested 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 ArcMap 10.1 where it was visualized as a flood inundation map with the use of the extension of HEC-GeoRAS. These maps have been 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 Sirajgonj district suffered highest inundation in the month of August. On 24 August 2014, Shahjadpur Thana, Ullah Para Thana, Tarash Thana and Chauhali Thana were completely inundated with flood water and other thana named Kamarkhand Thana and Royganj Thana were inundated partially. Inundation map was 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 here, flooding due to breaching of embankment or other reasons were not considered in her study.

Khan (2017) found that the flood starts in Jamuna River in early June and sometimes in early August. The flood of 2004 showed a massive inundation. As per their model result, it is seen that flood starts from third quarter of June and peak occurs at late July. Sirajgonj, Tangail and Bogra were mostly affected by that flood. 2007 flood seemed to be more extensive than the flood of 2004. Here the peak occurs lately nearly at mid-August. The flood sustained for a long period compared to the other ones according to the flood map Simulated. From model simulation it is seen that peak occurs at the end of September and its duration was much short compared to 2004 and 2007.

2.3 Flood Statistics of Ghaghat River

Ghaghat River is a distributary of the Teesta river of Bangladesh carrying a significant amount of flow to the Brahmaputra River (Ahmed, 2010). It flows through Nilphamari, Rangpur and Gaibandha district. Flood along the Ghaghat River frequently occurs during the rainy season (BWDB, 2011). Nilphamari district was not affected by this floods but significant flooding observed in Rangpur and Gaibandha district (as showed earlier in figure 1.1). As flood affected the major city area of Rangpur and Gaibandha district so necessary steps should be taken to mitigate the flood from this region. The district map of Rangpur and Gaibandha has shown in figure 2.1.

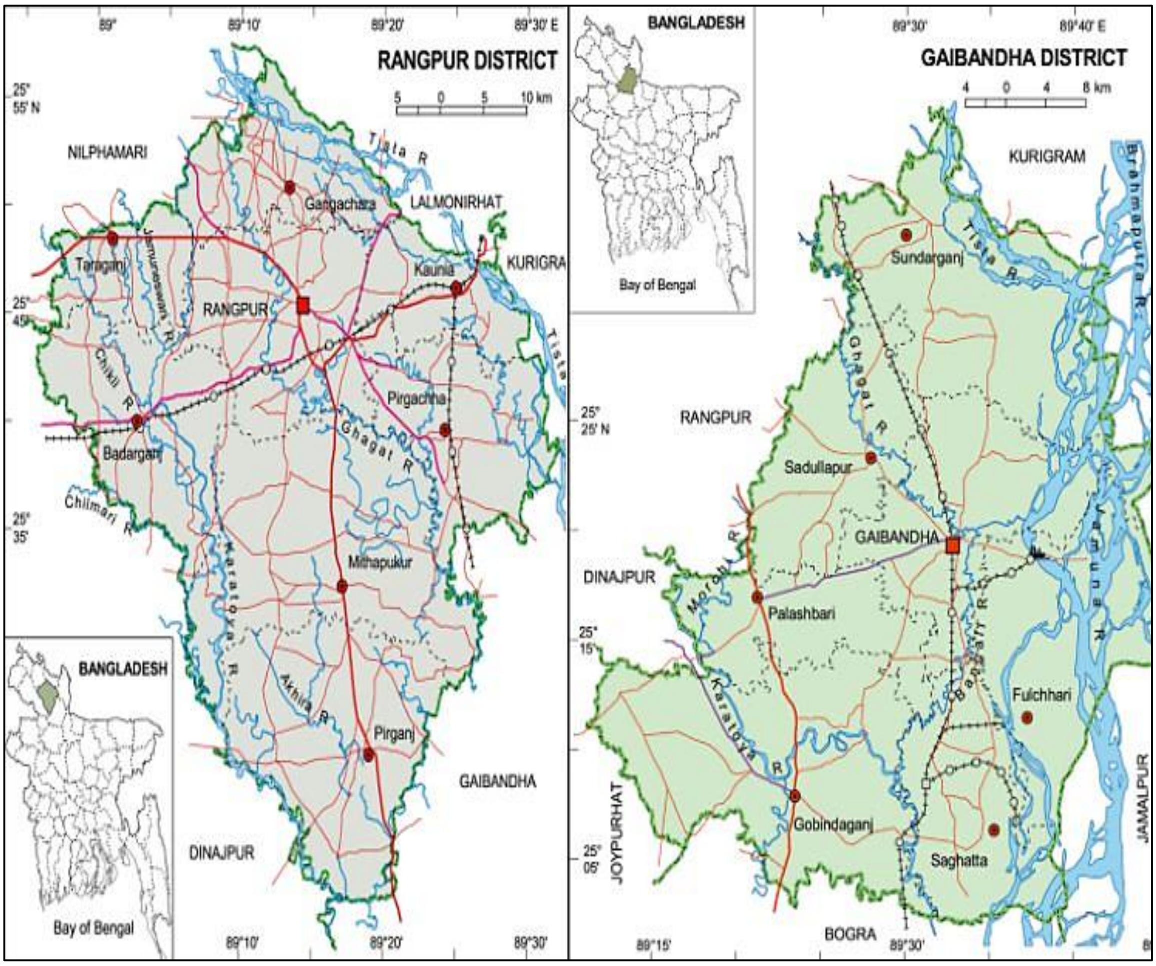

Figure 2.1: Rangpur and Gaibandha district map with Road Network
(Source: Rangpur and Gaibandha district portal of Bangladesh Government: https://bangladesh.gov.bd/)

Gaibandha and surrounding districts are notable among the flood affected districts of Bangladesh. It has been recorded that during the historical flood event in Bangladesh, the water level in Ghaghat River was above the danger level and caused flooding on the nearby floodplain. The danger level at Gaibandha (SW 97) is 21.7 m. Because of the danger level of water of Ghaghat River, the area was impacted in Gaibandha has shown in Figure 2.2.

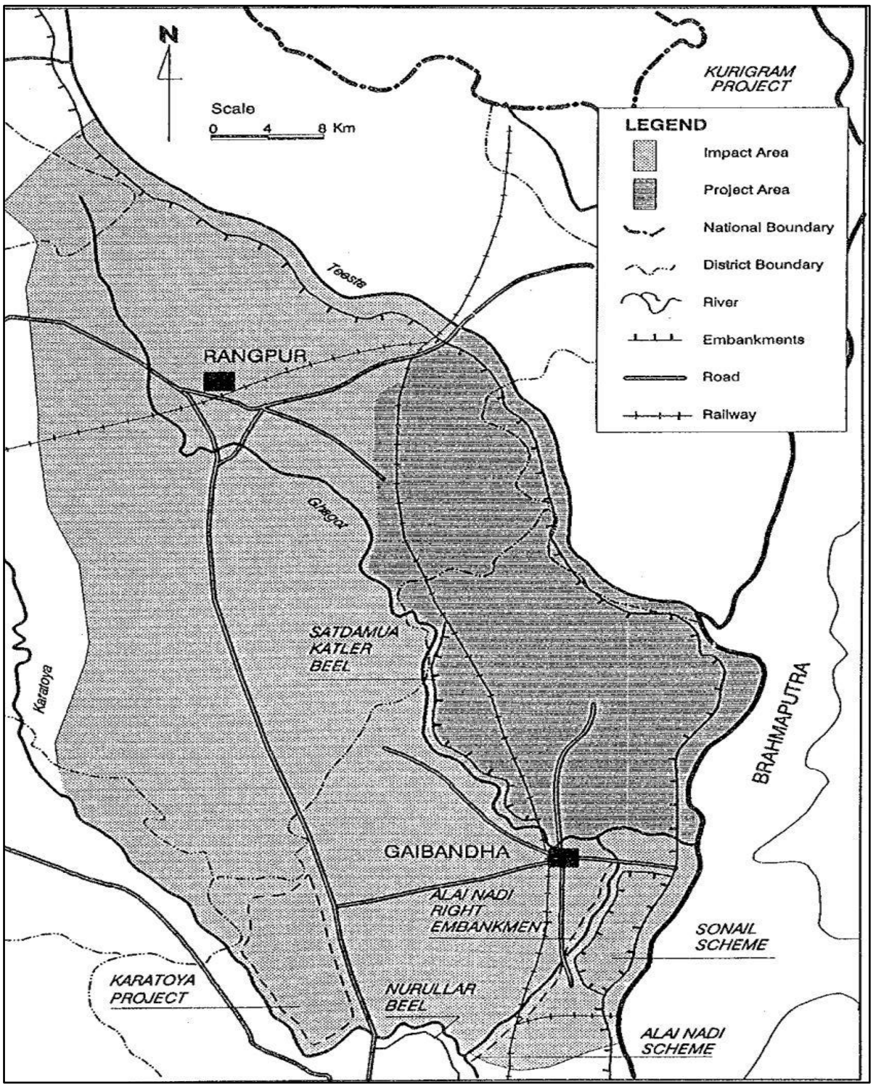

Figure 2.2: Flood impacted area on Gaibandha district for Ghaghat River
(Source: Gaibandha Improvement Project report, 1993)

During the devastating floods of 1998 and 1988 in Bangladesh, the water level in Ghaghat at Gaibandha (SW 97) was 21.7 m exceeding the danger level. The peak water levels of the Ghaghat River during monsoon are documented in different Annual Flood Reports of FFWC. Figure 2.3 showed the water level at Gaibandha (SW 97) of Ghaghat River for the flood year 1988, 1998, 2004, 2007, 2008, 2009, 2011-2015, 2017 and 2019 was above the danger level.

In 2011, the WL of Ghaghat River at Gaibandha showed a similar trend to that of the Jamuna at Sirajgonj and Brahmaputra at Bahdurabad, flowed near to the DL (Danger Level) during 3rd week of July to 3rd week of August. It flowed above the DL for 4 days from 21st July to 24th July with peak of 21.81m on 22nd of July, which was 11cm above its DL (21.70m) at this point.

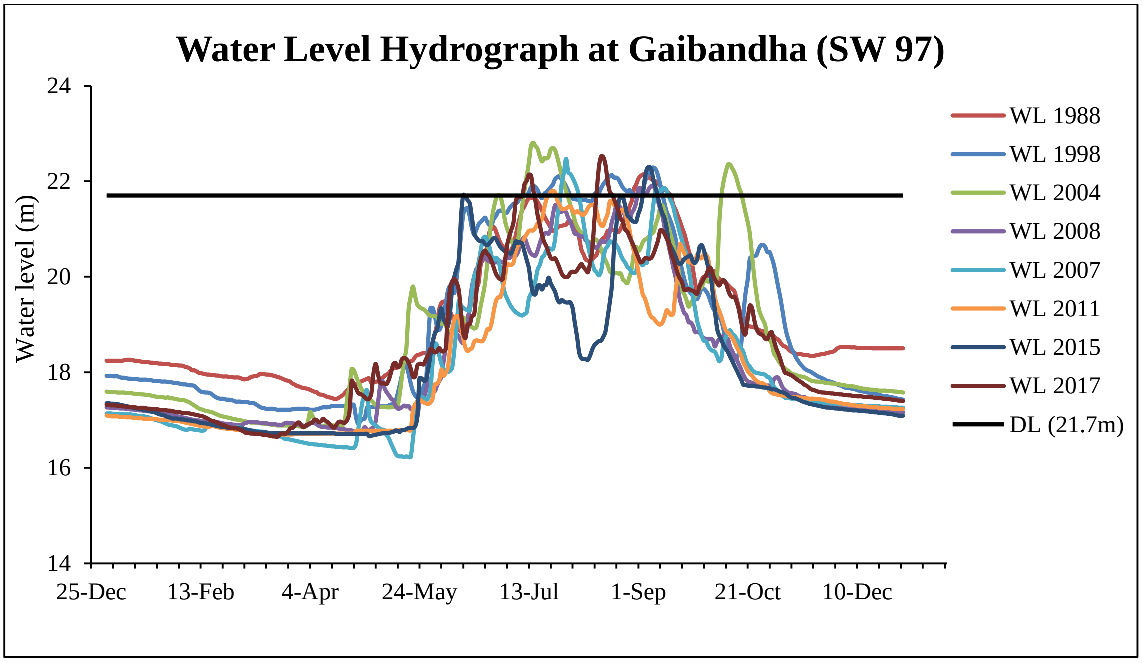

Figure 2.3: Comparison of flood hydrographs of Ghaghat River at Gaibandha

In 2012, the WL of Ghaghat river at Gaibandha crossed DL for three times. It flowed above the DL for 15 days during end of June and beginning of the July with peak of 22.35 m on 1st July, which was 65cm above its DL (21.70m) and again end of July and end of September.

In 2013, the WL of Ghaghat River at Gaibandha crossed DL once during the monsoon 2013. It flowed above the DL for 4 days; between 9th July to 12th July; with peak of 22.17 m on 10th July, which was 47cm above its DL (21.70m).

In 2014, the WL of Ghaghat River at Gaibandha crossed the DL at 18th August 2014 and flowed above the DL for 14 days: between 18th August to 1st September; with peak of 22.36 m on 10th July, which was 66cm above its DL (21.70m).

In 2015, the WL of Ghaghat river at Gaibandha crossed DL twice during the monsoon 2015, firstly in mid of June for two days and secondly in the beginning of the September for six days. It flowed above the DL for 8 days with peak of 22.33 m on 6th September, which was 63cm above its DL (21.70m).

In 2016, the WL of Ghaghat river at Gaibandha did not crossed DL (21.70m) during the monsoon 2016. It attained peak water level 22.61 m which was 9 cm below DL (21.70m).

In 2017, the WL of Ghaghat River at Gaibandha crossed the DL (21.70m) for 2 times during the monsoon-2017. It attained peak water level 22.55 mPWD on 15th August which was 85 cm above DL (21.70m). During the whole monsoon, this station flowed above DL for 15 days.

In 2018, the WL of Ghaghat River at Gaibandha during the monsoon-2018 attained peak 21.51 mPWD on 17th September which was 19 cm below DL (21.70m). During the whole monsoon, this station flowed below DL.

In 2019, the WL of Ghaghat River at Gaibandha during the monsoon-2019 attained peak of 22.64 mPWD on 18th July which was 94 cm above DL (21.70m). This station flowed above its DL mark for 16 days during the time and flowed below DL during the rest of the monsoon.

2.4 Studies Related to Flood in Ghaghat River

Though a few studies of flood scenarios of the study area have done, but flood inundation mapping and flood mitigation of Ghaghat River has not done yet.

Shah and Werner (2012) studied the response to flood warnings taken by farmer households in an agricultural area in the Urai union Gaibandha in Bangladesh. Interviews with experts and a survey of farmer households were used to analyze the flood early warning system and the response to warnings during the 2007 flood event. Results show that warnings received from multiple sources increased confidence as information could be cross-checked, despite that information originating from a single source. Responses included saving livestock, family members and household assets. It was found that the response was influenced mainly by the source(s) of warnings, the quality of information, visibility of floods, the personality of the warning recipient, as well as the ability to bear the costs. Differences in these factors were found, depending on the farmers located in high or low flood-prone areas.

Few studies had done on the morphological process of Ghaghat River such as Gaibandha Improvement Project, FAP-2 by JICA in 1993. In this study, morphological condition of Ghaghat River had observed because of noticing the flooding problems of Ghaghat River. According to this study and noticing the flooding problems some mitigation options has been proposed.

That's why, this study has been designed for the flood inundation mapping and mitigation of flood of Ghaghat River and its floodplain using HEC-RAS.

2.5 Previous Studies and related Research on Flood Mitigation around the World

Tingsanchali (2012) described concepts, policy, plan and operation on integrated urban flood disaster and risk management. In most developing countries, flood disaster management activities are handled by government. Participation of non-governmental agencies and private sectors are very limited. Flood disaster management in developing countries is mostly reactive responding to prevailing disaster situations (emergency response and recovery). Reactive response should be changed to proactive response to increase effectiveness of management and reduce losses of life and properties. Proactive disaster management requires more participation from various governments, non-governmental and private agencies and public participation. It involves more effort and time, more budget, equipment, facilities and human resources which leads to integration of flood disaster management for both long term and short-term activities. Strategic framework on integrated flood disaster management includes four cyclic steps namely: 1) preparedness before flood impact such as flood forecasting and warning; 2) readiness upon flood arrival; 3) emergency responses during flood impact and; 4) recovery and rehabilitation after flood impact. Examples on urban flood disaster and risk management in Thailand are illustrated and discussed. Conclusions and recommendations for further improvement are provided.

Subia (2019) aimed to investigate the flood prevention and mitigation initiatives of Cabanatuan to gain information that served as the basis for the development and integration of flood prevention and mitigation initiatives in the City. The researcher used the descriptive research design with questionnaire as the main tool to gather information from the 110 barangay residents and officials, Local Government Units (LGU) and Cabanatuan City Disaster Risk Reduction and Management Office officers (CCDRRMO) of the City. The study found out that: a. Cabanatuan City is vulnerable to flooding's; barangays in Cabanatuan that are more flood physical vulnerable are Aduas Centro, Aduas Norte, Aduas Sur, Bagong Sikat, Bakero, Bakod Bayan, BantugBulalo, Barlis, Barrera and Balite; b. Heavy and prolonged rainfall, clogged river, canals, creeks and streams, lack of preventive infrastructure and facilities and poor implementation of waste management system were the possible leading causes of flooding in Cabanatuan City; c.

The flood prevention and mitigation initiatives as to control over the river and control over the land were moderately implemented while other mitigation measures that had been done by the City Government were properly implemented; d. There is no significant difference in the responses of the three groups of respondents regarding the flood prevention and mitigation initiatives done by the Cabanatuan City government; e. Monthly seminars regarding floods for proper awareness and readiness, strict implementation of the law, appropriate coordination with community and government authorities and better flood prevention and mitigation plan were the suggestions of the respondents towards a flood-free city.

Frederick (1991) designed to reduce the effects of floods have focused on such structural measures as the construction of dams or embankments (polders, levees, etc.). Many developments expert’s question whether large-scale flood control projects are economically suitable for the least-developed countries, since they increase the country's debt significantly for little economic return. Interest has recently increased in alternative strategies for protecting the floodplains especially in rural areas. These strategies can often be adopted or modified into a national ‘living with floods’ strategy to encourage people to adapt to floods and to capture their benefits for economic development. Where this strategy has been applied it has been cost-effective, easy to implement and compatible with the environment. More important, it can be incorporated into long-term development programs.

2.6 Previous Studies and related Research on Flood Mitigation in Bangladesh

Humayain (2019) analyze the existing flood research conducted so far in Bangladesh. Flooding is a regular disastrous event in Bangladesh as it causes serious social and economic losses and damages in the different parts of the country in every year. Moreover, at least one- third of the country is vulnerable to flooding. Sufferings of people due to flood are beyond imagination. Despite its recurrent nature and devastation, the comprehensive research on flooding in Bangladesh has been limited. This study used a systematic literature review to understand the flood research in Bangladesh. This review clearly suggests that research related with flood modelling, forecasting and flood management is much less emphasized. This review of flood research helped the authorities to have an overview of important aspects of flood during planning of mitigation measures and management projects. This in turn, has facilitated mitigation and adaption measures to better respond to the country's chronic flood problem.

Ali (2018) analyze different types of floods which have caused enormous damage to properties and lives, managing floods still remains a challenging task. Flood management is a multi-sectoral activity due to its complexity, scale, and multidisciplinary nature. Sirajganj district can be regarded as one of the most vulnerable areas in Bangladesh and hence a study was carried out for Sirajganj district to provide guidelines to combat challenges to flood risk management. The flood frequency analyses at three river stations using water level data were carried out, the flood inundation map for different return periods and a flood depth versus damage curve are plotted to address the vulnerable areas and dam-ages, and to help design flood mitigation structures. It can be inferred that damages have been proportional to return period since the risk is a function of hazard, vulnerability, and exposure. Both structural and non-structural measures including rejuvenation of the Jamuna River and low-cost flood resistant building approaches for flood affected char (island) people are suggested along with a few recommendations to mitigate floods in the study area. The government, Non-governmental organization (NGO), funding agencies, and trans-boundary countries should come forward to mitigate flood hazards to improve the livelihood of the affected people.

2.7 Summary

The review of findings of previous study is very much needed before undertaking any research work. Therefore, the literature review of the previous studies around the world as well as in Bangladesh has been carried out in this chapter. It is necessary to acquire a clear concept about the previous research works which is the base of the present research and also to identify the scope of the work. Based on these literature review works; findings of the results are as follows: the hydro-dynamic modulation of the different river is well documented in the literature.

From the above literature reviews, it can be summarized that though the world's research on the flood inundation mapping are quite in a vast stage, flood mitigation is still in an early stage in Bangladesh. A few studies on mitigation have done, but flood inundation of Ghaghat River has not been studied yet, let alone its mitigation options due to inundation. Hence, the flood mitigation of Ghaghat River considering new concepts scenarios based on inundation mapping are very necessary. That's why, this study is designed for the flood inundation mapping and flood mitigation of Ghaghat River and its floodplain.

Among many numerical hydrodynamic models, open source HEC-RAS has been chosen to carry out this study. Because the performance of HEC-RAS 1D is quite acceptable for one-dimensional simulation of artificial channels or simple reaches. On the other hand, the HEC-RAS 1D-2D coupled model is highly recommended for flood inundation modeling which includes floodplains as 2D part and river as 1D part. Hence, in this study, for flood mitigation of Ghaghat River Floodplain, HEC-RAS 1D-2D coupled model is used.

CHAPTER 3
STUDY AREA AND THEORETICAL BACKGROUND

3.1 General

Flood is a natural process that occurred when the water rises to overflow land that is not normally submerged (Ward, 1978). Those lands are sometimes referred as floodplain. Floods are among the most devastating natural (and sometimes human-produced) threats on Earth (Ohl et al., 2000), which involve inundations, i.e., submerged land from overflowing rivers and lakes when water overtops or breaks levees, from the sea because of high tides, and/or develop in otherwise dry areas due to accumulation of heavy rainfall.

3.2 Study area

The Ghaghat River (192 km long) is a tributary of Teesta river, originated at Jaldhaka in Nilphamari district and after passing through Gaibandha town (few km norths of Fulchhari Ghat) joins to the Brahmaputra river (BWDB, 2012). In the northern part of Bangladesh Ghaghat River is an important inland open water-body Its coordinates are 25°19'0" N and 89°37'60" E. Ghaghat River flow varies from 1 to 241m^3/sec.
The upstream of the Ghaghat is connected with the Teesta through breaches over a length about 7km, which was formed by the flood in 1988. Therefore, flood water and large quantities of sediment conveyed by the Teesta easily enter the Ghaghat. Besides, the excess flood water from the Teesta is retarded in the upstream reaches and sediment is deposited in the upstream riverbed and flood plain. Satdamua Katler Beel System funded by EIP provides a flood embankment on the left bank between Gaibandha and Bamandanga. But since the river reach upstream of Bamandanga is still unprotected by the flood embankment and there exit 11 openings such as bridge and culverts along the existing railway embankment between Kaunia and Bamandanga, flood water from the Ghaghat-Alaikumari intrudes into the GIP area (North West Regional Study (FAP2)).

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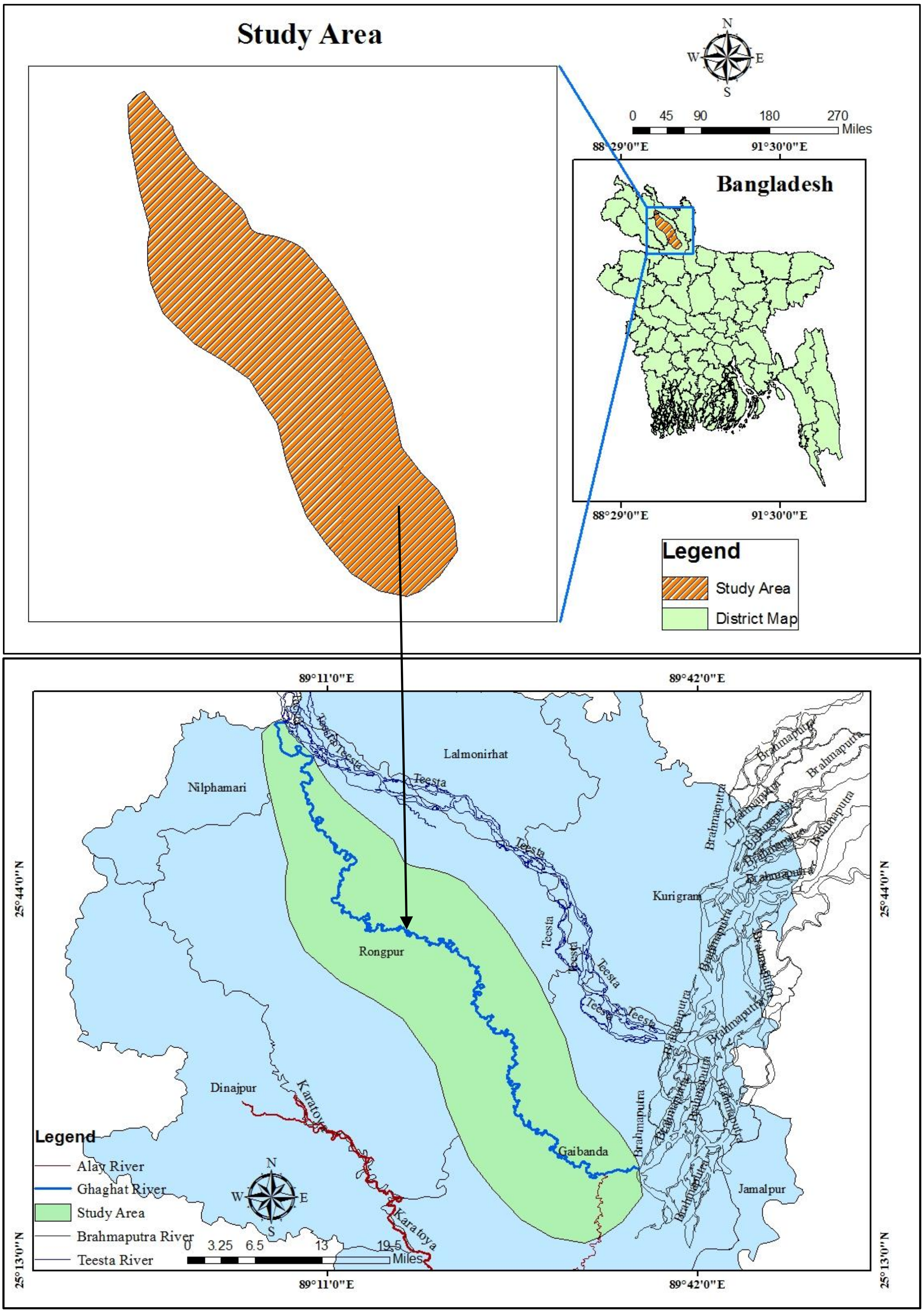

Figure 3.1: Identification of Study Area

Study area has been identified by delineation of watershed of Ghaghat River, observation of flood inundation map of FFWC and Google Earth image and analysis of satellite image from previous year.

Satdamua Katler Beel System funded by EIP provides a flood embankment on the left bank between Gaibandha and Bamandanga. But since the river reach upstream of Bamandanga is still unprotected by the flood embankment and there exit 11 openings such as bridge and culverts along the existing railway embankment between Kaunia and Bamandanga, flood water from the Ghaghat-Alaikumari intrudes into the Gaibandha Improvement Project area (North West Regional Study (FAP2)).

The existing flood embankment on the left bank is severely eroded on both side slopes and the stability of flood embankment is considered to be rather low against seepage and sliding considering the long duration of flood in the downstream reach.

BWDB provided the food embankment with about 1m height and 1m crest width along Gaibandha to Sadullahpur road on the right bank before 1987. There exit many excavated portions and severely eroded slopes in the flood embankment, and therefore it has easily allowed the intrusion of flooding water from these portions. The inhabitants claim that the flooding situation in the area became more severe than before the construction of the left embankment of the Ghaghat. The inundation depth in the area is 1m in normal year and in 1987 all the area was inundated.

There are many beel areas on the right bank surrounded by Ghaghat, National Highway, Alai river and Bangali in which the flood water spilling from the Ghaghat through the Naleya river is retained and cause drainage congestion due to insufficient capacity of drainage rivers and khals into the Karatoya/Bangali.

Water Level

Figure 3.2 shows a long profile along the Ghaghat River for a typical higher flow year, 1987. The impact of the simulation is to reduce peak water levels by over a meter throughout almost the entire reach. This impact is pre-dominantly due to the sealing of the Teesta right embankment upstream of Kaunia, thereby preventing Teesta water contributing to flows in Ghaghat. The overall hydrograph shapes in the upper and middle reaches of Ghaghat also showed a much less peaky form after the sealing of the TRE as the flows result from rainfall-runoff within the catchment area only.

Figure 3.2 also illustrates the impact on water levels in the Alai river of constructing a regulator at the head of this river. The construction of this regulator has no significant impact on water levels in the Ghaghat since at the point where the Alai river flows from the Ghaghat water levels are determined by backwater effects from the Brahmaputra. With the regulator in place, water levels are reduced by about 2m below the confluence between the Ghaghat and Alai.

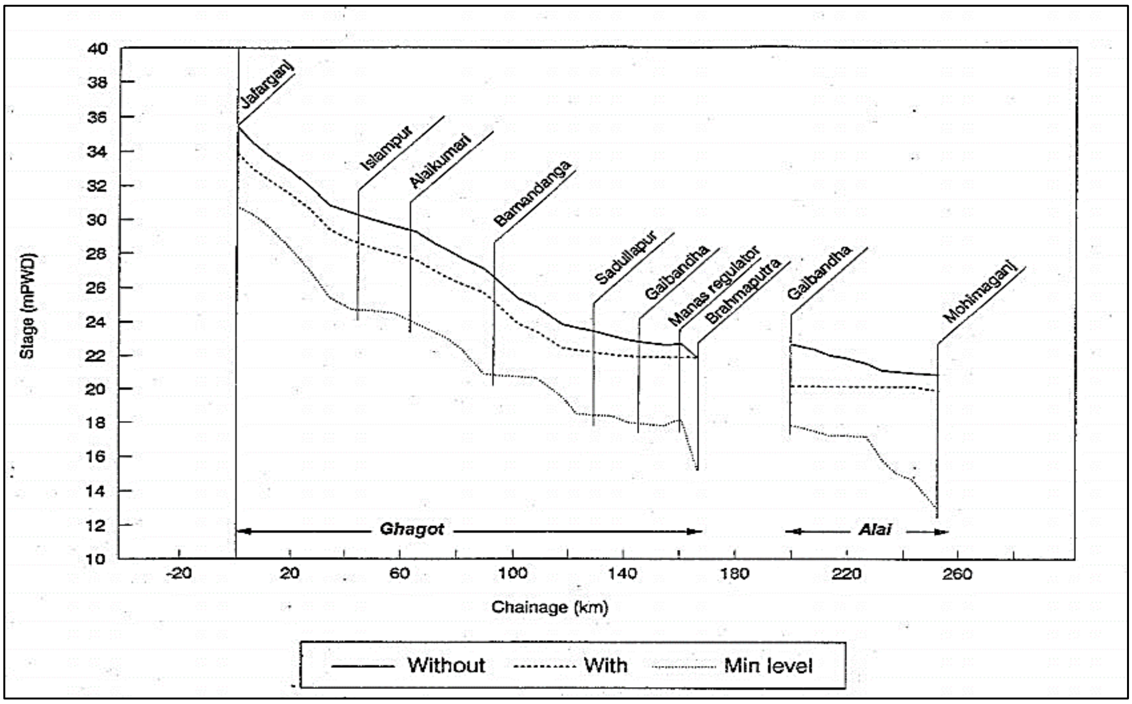

Figure 3.2: Long profile (1987) on Ghaghat and Alai River with and without constructing a regulator at the head of Alai River (Source: North West Regional Study (FAP2))

Near the confluence with the Karatoya water dominates. The Alai river regulator would effectively remove problems of spillage on its right bank and allow the rainfall-runoff from the surrounding area to drain more freely down the Alai.

Discharges

The peak discharge in the Ghaghat, Alai Kumari and the discharge channels which enter the north of the GIP area are significantly reduced by the sealing of the TRE. This reduction in flow is reflected throughout the Ghaghat river system. The peak discharge in the Alai river is also greatly reduced by the construction of the regulator at the head of this river.

In Communities along the Ghaghat near the beel the people claimed that siltation of the Ghaghat was now causing major problems and in the last three years had seriously damages the Aman production, vegetable and their homes. They were fully cognizant that slow meandering rivers cause lots of spillage on to the land. They also stated, however, that embankments were not the answer since they would increase the levels of deposits by keeping them in the main channel. What they wanted was regular re-excavation, to be carried out by the villagers as a source of local employment (North West Regional Study (FAP2)).

Ghaghat Left Embankment

The Ghaghat Left Embankment (GLE) is constructed through two projects; on is Satdamua Katler Beel project funded by EIP and the other is Gaibandha Town Protection. The Satdamua Katler Beel project is providing flood embankment with total length of about 35km which consists of new flood embankment 6km long and re-sectioning of road embankment 29km long on the left bank from Gaibandha to Bamandanga. The project is scheduled to be completed in 1992/1993 fiscal year. Also, Gaibandha Town Protection scheme built a flood embankment with a length of 5km from the existing road bridge to the confluence of the Manos river on the bank along the Gaibandha town area to prevent flooding from Ghaghat and Manos.

The GLE has a height of 0.5m to 4.6m, a crest width of 1.0m to 5.0m, and side slope of 1:0.4 to 1:2.5 at the country side and 1:0.9 to 1:2.6 at the river side. But in the downstream reach from the confluence of the Manos, flood embankment is not provided. The side slope if GLE is designed and constructed at 1:2 but the existing slopes are less than designed at most parts. (North West Regional Study (FAP2))

There are nine regulators along the GLE. Manos regulator, discussed above in relation to the Brahmaputra Right Embankment, aims to draining out flood water of the Ghaghat and Manos, South Gagoa regulator for the area of Gaibandha Town Protection, and others for an area of 6,200 ha of the Satdamua Katler Beel project which is bound by the railway line and the Ghaghat.

Sonail Embankment

The Sonail Embankment scheme is a completed project funded by EIP. The total length of Flood embankment is 19.4km on the left bank along the Alai and on the right bank along the Ghaghat, of which 4 km is located along the Ghaghat and its’ connected with the BRE. The Sonail embankment along the Ghaghat has a height of 2.2 m to 3.4 m, a crest width of 3.0 m to 5.4 m, and side slope of 1:1.7 to 1:2.9 at the country side and 1:1.8 to 1:2.4 at the river side.

Most of the flood from the Ghaghat flows into the Alai during peak-monsoon season since the capacity of the Manos regulator depends on the water levels of the Brahmaputra and it is difficult to drain out flood water of the Ghaghat through the Manos regulator during this period. On the other hand, the flow capacity along the Alai is less than 100 m^3/s and therefore not only the project area of the Sonail Embankment scheme but also the right bank area suffers severe inundation due to drainage congestion. (North West Regional Study (FAP2))

3.3 Floods of Bangladesh

Floods have devastated millions of people in South and East Asia. One of the country most severely affected has been Bangladesh, where at least a quarter of the country was inundated. Almost 50% of the Bangladeshi population is employed in the agricultural department, specifically focusing on rice (FAO, 2015).

3.3.1 Flood and Types of Flood

About one-fifth to one-third of the country is flooded to varying degrees each year during May through September when about two-thirds of the food grain (mainly rice) are produced. Such a large extent of flooded area is due to extreme flat topography are shown in figure 3.3. The causes of natural floods are briefly mentioned below.

River Flood: The main source of flooding is the bank overflow from the major rivers the Ganges, the Brahmaputra and the Meghna, and their tributaries and distributaries during June to September. A broad strip of land adjacent to the rivers is subjected to this type of flood as shown in figure 3.3.

Rainfall Flood: About 80% of annual rainfall in Bangladesh occurs during May to September when the rivers flow at high stage due to huge inflow of water from catchments outside the country. As a result, drainage is impeded. Besides high intensity and long duration rainfalls cause local flooding when the local river cannot drain quickly.

Flash Flood: In the northern and eastern hill streams, flash flood occurs during the pre-monsoon months of April and May. Flash floods in the NE region cause damage to dry-season the Boro rice crop just before or at the time of harvesting and also to towns and other infrastructures.

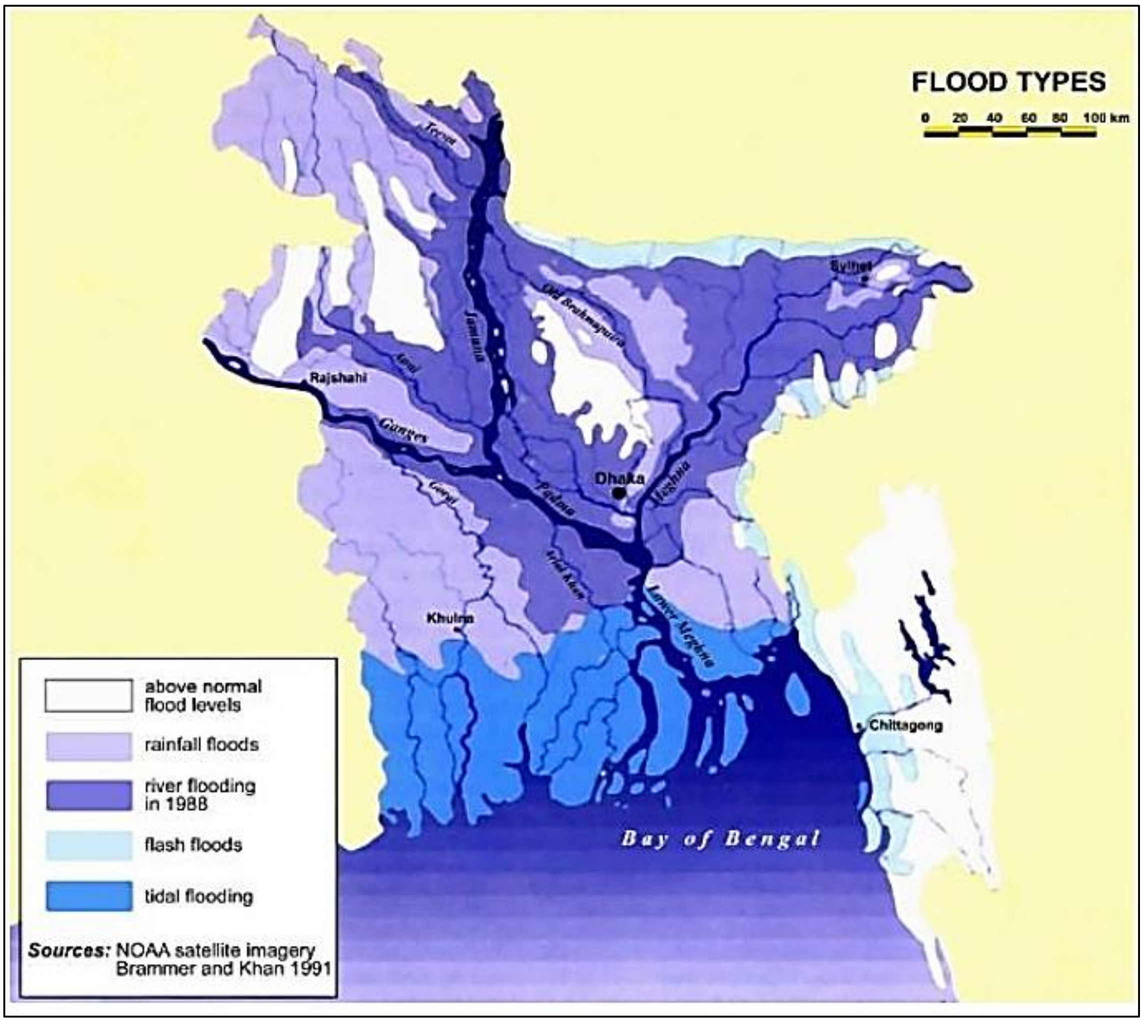

Figure 3.3: Types of Flood in Bangladesh (Source: FFWC)

Tidal Flood: The areas adjacent to estuaries and tidal rivers in the SW and SC regions get flooded twice a day due to astronomical tide from the Bay of Bengal. During spring tide which occurs fortnightly, large area is flooded by tidal water. The coast of Bangladesh is subjected to astronomical tide which originates in the Indian Ocean and travels through the Bay of Bengal. The tides are predominantly semidiurnal that is the tidal period is 12 hours 25 minutes. In the SW region of Bangladesh, 15 tidal action is experienced up to 225 km inland in the wet season and 325 km inland in the dry season (Halcrow et al., 1993c). Most of the area in the SW region is below the high-water level of spring tide. Extensive coastal embankments and polders have been constructed in the region to prevent tidal flooding. The average tidal range in the area varies from approximately 3.0 m on the coast at the entrance of Passur River to 0.5m at 275 km inland. In addition to daily tidal fluctuation at the coast, there are half yearly variations in sea level of 60 to 80 cm due to seasonal changes in salinity and atmospheric pressure (Halcrow et al., 1993c).

Storm-surge Flood: The storm surges due to tropical cyclones in the Bay of Bengal occasionally cause severe disaster in the coastal areas. This flood can occur during April to June and September to November. Approximately 12,000 sq.km. Coastal land is prone to cyclonic storm surge floods. Occasional storm surge floods generated by tropical cyclones in the Bay of Bengal cause severe disaster in the coastal region of Bangladesh. More than 700,000 people have been killed by floods due to 15 cyclonic storm surges since 1960. Approximately 9,100 sq.km. of coastal area, which is more than 6% of the total area of Bangladesh, is prone to flood depth of at least 1 m. Intrusion of storm surges in the SW region can be up to 55 km while in the Chittagong area it can be up to 15 km. Estimated surge depths of 100 year return period are 7.8, 5.2 and 4.5 m at the entrance of the Lower Meghna estuary, at the SW region coast and at Chittagong coast respectively (Chowdhury, 1994b).

3.3.2 Different Causes of Floods in Bangladesh

The factors responsible for the recent low frequency floods in Bangladesh can be analyzed in terms of short-term (immediate causes) and long-term processes. Evident phenomena that take place prior to and during floods, which can easily be related as plausible causes for floods, are termed short-term processes. On the other hand, the slowly occurring phenomena which cannot be tied to the flood problem directly are termed long-term processes.

Short-term Causes

(a) Monsoon downpour: An increased amount of precipitation can cause flooding. An above normal monsoon downpour in the Ganges-Brahmaputra-Meghna drainage system is thought to be the primary cause of the 1988 flood in Bangladesh (GOB and UNDP, 1989; Brammer, 1991). It is not known, however, if the heavy precipitation is actually an effect of other processes such as the greenhouse effect or destruction of forests in the upstream region.

(b) Synchronization of Flood Peaks: The synchronization of flood peaks for the major three rivers took place within a two-week time period, causing a sudden increase in water level in virtually all areas of the country (GOB and UNDP, 1989; Brammer, 1991). While the synchronization of flood peaks can explain the cause of the 1988 flood, it fails to explain the reason for an overall increased propensity for low frequency floods in recent years such as occurred in 1974, 1984, 1987, and 1991. The answer might lie in other long-term processes that reduce the water carrying capacity of the drainage system and decrease land elevation with respect to the base level of the rivers in Bangladesh.

Long-term Causes

(a) Local Relative Sea Level Rise: The ultimate destination of all rivers is the ocean. The land elevation is measured with respect to sea level in an area. Therefore, any change in sea level causes land elevation to change. At the present time sea level is rising globally (Pilkey et al., 1989). If sea level rises in an area at a rate faster than the rate of land aggradation due to sedimentation, then land elevation decreases. Any decrease in land elevation can cause increased inundation by rivers overflowing at bank-full stage. The rate of local relative sea level rise is 7 mm/year around the coastal areas of Bangladesh (Emery and Aubrey, 1990). An increase in sea level raises the base level of rivers, which in turn reduces the gradient of river flow. As a result, the discharge of rivers decreases as the water flow becomes sluggish, creating a backwater effect further inland. The backwater effect caused by sea level rise can result in more flooding of land from "piled up" river water inland (Warner, 1987). This certainly seems to be one of the reasons for the increase in flood intensity in recent years in Bangladesh.

(b) Inadequate Sediment Accumulation: The only way for land to counter the effects of a rising sea is for sediment to accumulate at a rate that is sufficient to keep pace with the rate of sea level rise. Limited data show that the average sediment accumulation rate for the last few hundred years in the coastal areas of Bangladesh is 5-6 mm/year, which is not enough to keep pace with the rising sea level (Khalequzzaman, 1989). As a result, net land elevations must have been decreasing over time, resulting in more flood inundations.

(c) Subsidence and Compaction of Sediments: Sediments on a delta plain are rich in decomposed organic matter, and are subject to compaction due to dewatering and the weight of the overburden. Most deltas subside due to the weight of the thick sediment layer. Subsidence along with compaction reduces land elevation with respect to the rising sea level (Pilkey et al., 1989). Even though the rate of subsidence and compaction are not yet well documented, based upon our knowledge about processes active in other deltas it can be assumed that Bangladesh's delta is also undergoing subsidence and compaction.

(d) Riverbed Aggradation: Due to relatively higher settling velocity, the large-grained sediments are deposited near the source area on the riverbeds, forming sand bars. The river gradient decreases rapidly if sedimentation continues on the riverbeds. Because of low gradients and high sediment loads, the riverbeds of most of the rivers in Bangladesh aggrade very quickly. Riverbed aggradation is most pronounced for the Ganges and its distributaries. From the border with India to the point where the Ganges meets the Brahmaputra, the riverbed has aggraded as much as 5-7 meters in recent years (Alexander, 1989b). Riverbed aggradation is so pronounced in Bangladesh that changes in riverbed level can be observed during one's lifetime. For example, the Old Brahmaputra was navigable for steamers only about 30 years ago, and is presently an abandoned channel. This situation is true for many other distributaries of the Ganges and Meghna such as the Madhumati, the Bhairab, the Chitra, the Ghorautra, etc. Riverbed aggradation reduces the water carrying capacity of rivers, causing them to overflow their banks. This recent increase in riverbed levels must have contributed to the increased flooding propensity in Bangladesh.

(e) Deforestation in the Upstream Region: A rapid increase in population in the Indian Subcontinent over the course of the present century has resulted in an acceleration of deforestation in the hills of Nepal to meet the increasing demand for food and fuel wood (Bajracharya, 1983; Ives, 1989; Sharma, 1991). Deforestation of steep slopes is assumed to lead to accelerated soil erosion and landslides during monsoon precipitations. This in turn is believed to contribute to devastating floods in the downstream regions such as in Bangladesh (Hamilton, 1987; The New York Times, 1988; Alexander, 1989a).

(f) Damming of Rivers: Damming of a river reduces the velocity of water flow downstream from the dam. As a result of reduced velocity, the sediments carried by the river start to settle down faster on the riverbed, causing riverbed aggradation and in turn reducing the water carrying capacity of the river (Shalash, 1982). The Farakka Barrage on the Ganges has already caused tremendous damage to the agriculture, navigation, environment, and hydrodynamic equilibrium in Bangladesh (Shahjahan, 1983; Siddiqui, 1983; Broadus et al., 1986; Khalequzzaman, 1989).

(g) Soil Erosion due to tilling: Ploughing makes the land surface more susceptible to soil erosion. Surface run-off can easily wash away the topsoil from cultivated land. This surface erosion reduces land elevation, which in turn increases flood intensity in an area.

The land elevations in Bangladesh must have been reduced over time due cultivation. Aside from this, the tilling on the mountain slopes of the Himalayas is thought to be responsible for massive soil erosion in Nepal (Dregne, 1987; Thapa and Weber, 1991; Sharma, 1991) that eventually causes rapid riverbed aggradation in Bangladesh (Alexander, 1989a).

(h) Excessive Development: Rapid population growth creates extra pressure on the land of already overcrowded Bangladesh. Agricultural lands give way to housing developments and roads. This rapid development and urbanization must have aggravated the flooding problem in Bangladesh. Prior to urbanization there is a greater lag time between intense rainfall and peak stream flow. After urbanization the lag time is shortened, peak flow is greatly increased, and total run-off is compressed into a shorter time interval- favorable conditions for intense flooding. For example, in a city that is totally served by storm drains and where 60% of the land surface is covered by roads and buildings, floods are almost six times more numerous than before urbanization (Pipkin and Cunnings, 1983).

(i) Seismic (Earthquake) and neotectonics' Activities: Bangladesh lies on the Indian lithospheric plate, which is pushing against the Asian plate, causing growth of the Himalayas and occasional earthquakes in the region. Earthquakes cause movement of the land, and this can change the topography of the region and alter river courses. A sudden change in a river course can cause substantial flooding. For example, the Old Brahmaputra changed its course to its present location following an earthquake in the mid eighteenth century (Er-Rashid, 1978). The northern regions of Bangladesh are earthquake-prone (Morgan and McIntyre, 1958). Neo-tectonic activities (recent movements in the Earth's crust) are affecting river courses in the area. The Madhupur tract and the Barind tract are undergoing such neo-tectonic activities (Morgan and McIntyre, 1958). Most of the recent floods have been approximately simultaneous with earthquake activities. For example, the 1950 earthquake in Assam caused "swallowing" of the Brahmaputra, by causing to breach its banks and flood in the region (The Times of India, 1988). The floods of 1988 and 1991 also are coincident with earthquake activities in northern parts of Bangladesh (The Times of India, 1988; The New York Times, 1991). Recently, a powerful earthquake occurred on October 20 of 1991 in northern India, which was preceded by a flood in Bangladesh and was followed by another flood in the Ganges valley in India (The Philadelphia Inquirer, 1991). Floods can be both a cause of and an effect of an earthquake. Flood water places an extra hydrostatic pressure on unstable and mobile crustal blocks. If this extra pressure reaches the threshold strain limit along a fault zone or plate boundary within the Earth's crust, it can cause an earthquake to occur due to a sudden release of the strain energy accumulated over time. Similarly, an earthquake can change the surface drainage pattern and consequently the course of a river, causing sudden flooding in an area. Even though the cause and effect relationship between floods and earthquakes is not very clear, historic records suggest a relationship between these two phenomena.

(j) Greenhouse Effect: The world is about to enter a period of rapid warming. Should the greenhouse effect become a reality, the low-lying coastal areas were affected by a rising sea level of even greater magnitude (Milliman et al. 1989; Gable and Aubery, 1990). Bangladesh to be severely impacted by such an increase in sea level (Broadus et al., 1986; Khalequzzaman, 1989; Ali and Huq, 1989; Brammer 1989; Hossain 1989). Besides many other adverse environmental, economic, and climatic consequences (Huq and Ali, in press), the base level of all rivers has changed following any change in the sea level. The effect on flooding of a higher base level resulting from a rising sea level has already been discussed earlier in this section. The greenhouse effect has also increased the amount of rainfall and storminess, which has further aggravated the flood problem.

3.3.3 Statistics of Flood in Bangladesh

Flood is a natural phenomenon in Bangladesh and occurs on an annual basis. Rivers are large by global standards, and can inundate over 30% of the land mass at a time. Bangladesh is prone to serious and chronic flooding. Even in an average year 18% of the landmass is inundated and previous floods have affected 75% of the country (as in 1988). 75% of the country is below 10m above sea level and 80% is classified as floodplain as Bangladesh is principally the delta region of South Asia’s great rivers.

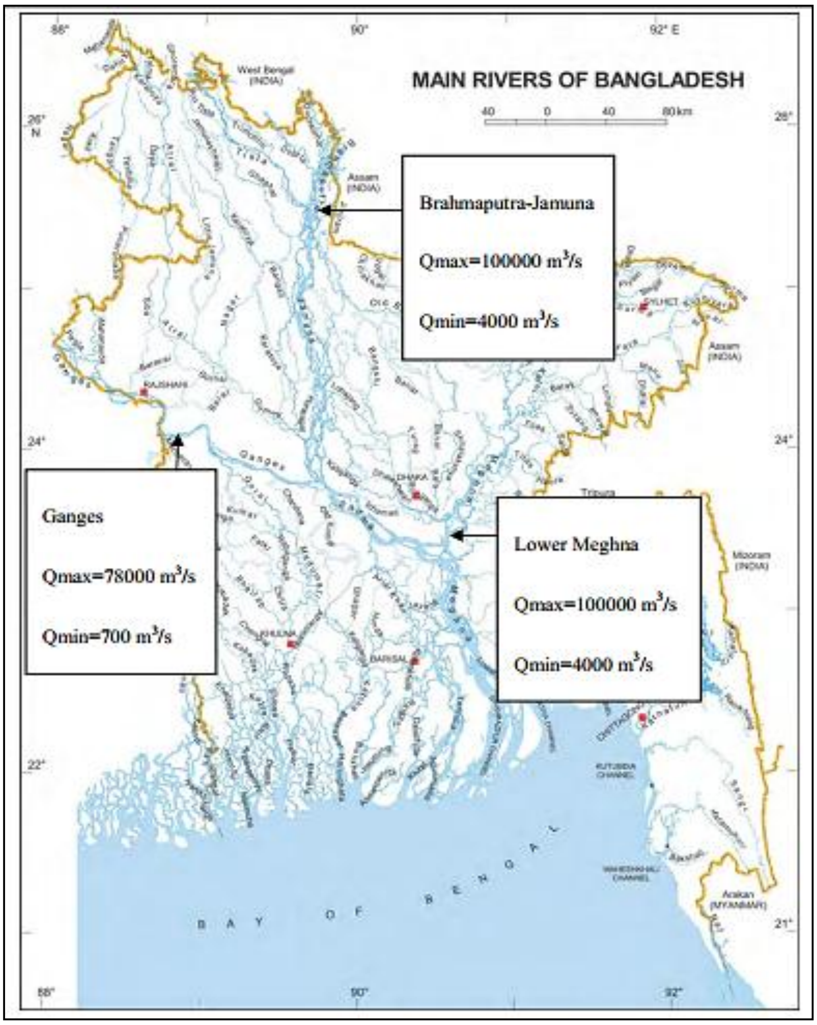

Figure 3.4: Discharges in the Ganges, Brahmaputra and Meghna River
(Source: www.lib.pmo.gov.bd, accessed on 13th January, 2018)

Bangladesh floods 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 and 2010. Flood statistics have summarized in table 3.1. Discharge of major River of Bangladesh has showed in figure 3.4. The catastrophic floods of 1987 occurred throughout July and August and affected 57,300 km^2 of land, (about 40% of the total area of the country shown in figure 3.5) and was estimated as a once in 30-70-year event. The seriously affected regions were on the western side of the Brahmaputra, the area below the confluence of the Ganges and the Brahmaputra and considerable areas north of Khulna. The flood of 1988, which was also of catastrophic consequence, occurred throughout August and September. The waters inundated about 82,000 km^2 of land, (about 60% of the area) and its return period was estimated at 50–100 years. Rainfall together with synchronization of very high flows of all the three major rivers of the country in only three days aggravated the flood. Dhaka, the capital of Bangladesh, was severely affected. The flood lasted 15 to 20 days. In 1998, over 75% of the total area of the country was flooded, including half of the capital city Dhaka.

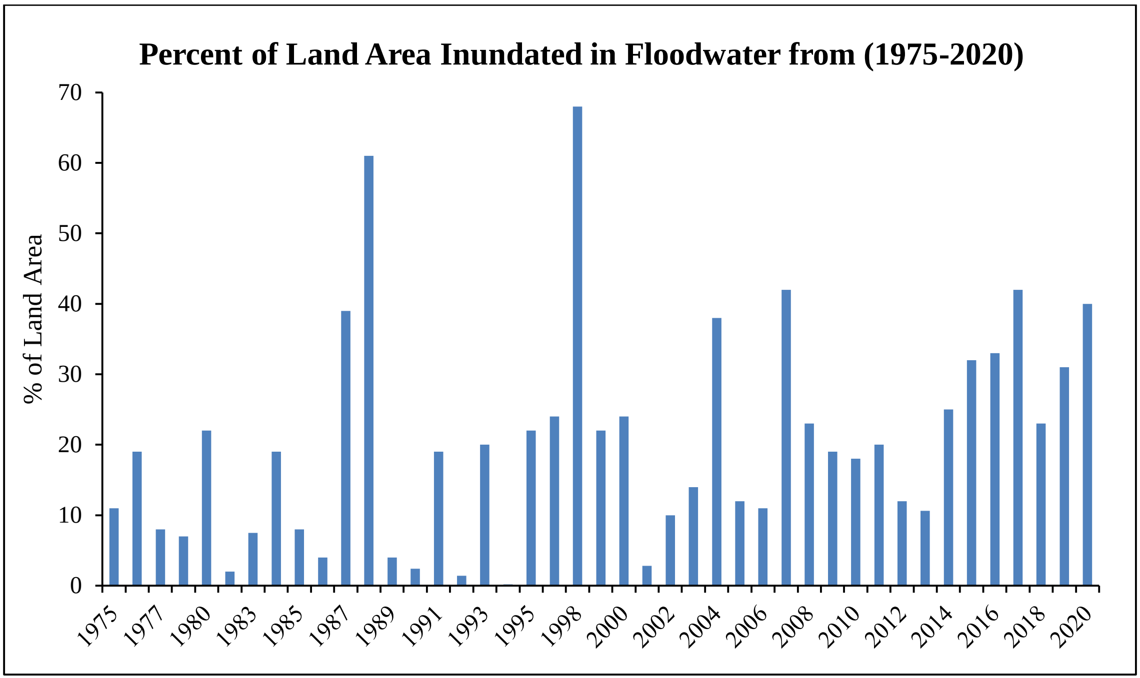

Figure 3.5: Percent of land area inundated (1975-2020) (Source: FFWC, 2020)

It was similar to the catastrophic flood of 1988 in terms of the extent of the flooding. A combination of heavy rainfall within and outside the country and synchronization of peak flows of the major rivers contributed to the river. 30 million people were made homeless and the death toll reached over a thousand. The flooding caused contamination of crops and 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. 700,000 hectares of crops were destroyed, 400 factories were forced to close, and there was a 20% decrease in economic production. Communication within the country also became difficult. The 2004 floods lasted from July to September and covered 50% of the country at their peak. At the time of the July 2004 floods 40% of the capital, Dhaka was under water. 600 deaths were reported and 30 million people were homeless. 100,000 people alone in Dhaka suffered from diarrhea from the flood waters. Bridges were destroyed, the death toll rose to 750 and the airport and major roads were flooded. This hampered relief effort. The damage to schools and hospitals was estimated at $7 billion. Rural areas also suffered, the rice crop was devastated as were important cash crops such as jute and sugar.

In 2007, more than half of Bangladesh was seriously affected by monsoon flooding. 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.

Table 3.1: Year-wise flood affected area in Bangladesh (FFWC, 2020) Historical report of Flood in the Study Area

Year	**Flood Affected area**		**Year**	**Flood Affected area**		**Year**	**Flood Affected area**	
	Sq.-Km	**(%)**		**Sq.-Km**	**(%)**		**Sq.-Km**	**(%)**
1954	36800	25	1978	10800	7	2002	15000	10
1955	50500	34	1980	33000	22	2003	21500	14
1956	35400	24	1982	3140	2	2004	55000	38
1960	28400	19	1983	11100	7.5	2005	17850	12
1961	28800	20	1984	28200	19	2006	16175	11
1962	37200	25	1985	11400	8	2007	62300	42
1963	43100	29	1986	6600	4	2008	33655	23
1964	31000	21	1987	57300	39	2009	28593	19
1965	28400	19	1988	89970	61	2010	26530	18
1966	33400	23	1989	6100	4	2011	29800	20
1967	25700	17	1990	3500	2.4	2012	17700	12
1968	37200	25	1991	28600	19	2013	15650	10.6
1969	41400	28	1992	2000	1.4	2014	36895	25
1970	42400	29	1993	28742	20	2015	47200	32
1971	36300	25	1994	419	0.2	2016	48675	33
1972	20800	14	1995	32000	22	2017	61979	42
1973	29800	20	1996	35800	24	2018	33941	23
1974	52600	36	1998	100250	68	2019	45747	31
1975	16600	11	1999	32000	22	2020	59028	40
1976	28300	19	2000	35700	24			

3.4 Flood Mitigation Strategies

The flood control measures and policies are to be directed to mitigate of flood damage, rather than flood prevention.

Approaches to Flood Control and Drainage: Many conventional flood mitigation measures like flood control reservoirs, flood diversion or flood by-passes are infeasible inside Bangladesh because of its extreme flat topography (Chowdhury, 1997). The flood control in the country has been based mainly on construction of embankments parallel to the river banks. In general, the following flood control and drainage approaches have been exercised in Bangladesh.

Full protection against river flooding in general, schemes designed to provide full protection aim to prevent spill of river waters by constructing embankments along the rivers, and to minimize internal flooding by the provision of appropriate drainage structures. Full protection is provided to protect agricultural lands and urban areas.

Partial protection against river flooding Partial protection from river flooding is provided by constructing low, submersible embankments. These are designed to delay pre-monsoon floods so as to ensure a safe winter rice harvest and create a favorable condition for HYV rice which requires a longer growing season. Submersible embankments are allowed to be overtopped during monsoon and remain submerged for the entire monsoon season. Along with the embankments, overflow spillways are used to withstand erosion during overtopping, and regulators are preferably incorporated to allow river water to enter protected area without spilling over the embankments when there is a big difference in water levels between the river and interior which can erode embankments. Partial protection by submersible embankments is favored in deeply flooded areas (Chowdhury, 1997).

Gravity drainage to reduce rainfall flooding unwanted rain water from behind the embankment or from within the pondered area is evacuated mainly by gravity flow through drainage regulators and sluices incorporated with the embankments. The regulators and sluices prevent backflow from high river levels into the low-lying areas during monsoon and drain the water from the area to be protected when the river water level gets below than that inside. Gravity drainage is favored in highland and medium highland areas and in area free from large variations in land level.

Pumped drainage to prevent rainfall flooding Drainage by pumps is expensive and has been provided in selected large Flood Control, Drainage and Irrigation (FCDI) projects to pump out accumulated rain water from the project area. Reversible pumps are generally used in order to serve both drainage and irrigation with drainage rate requirements much higher than irrigation rates. The pumped drainage is provided in areas consisting of higher percentage of deeply or moderately flooded areas.

Flood control measures are broadly divided into direct or structural and indirect or non-structural measures.

3.4.1 Structural measurements

Earthen embankments

Embankment systems limit flooding in protected areas and avoid flooding up to a "protection level." Embankments are the most frequently used form of flood control in Bangladesh as well in many other countries. To most people, constructing embankment alongside rivers which represented in figure 3.6 to prevent their water from entering habitations appears the most obvious way of controlling floods.

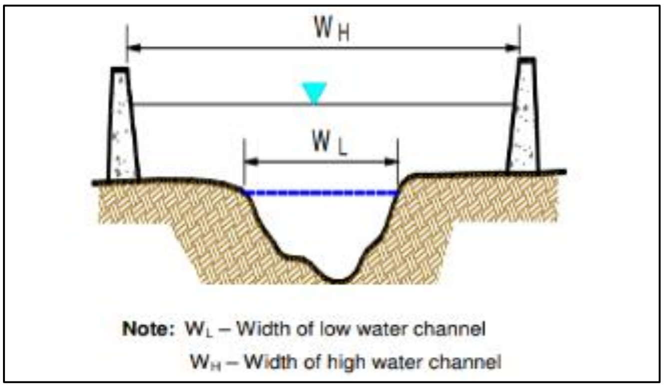

Figure 3.6: Embankment provided both side of river to protect flood prone area from overflow

A total of 5,695 km of embankments, including 3,433 km in the coastal areas, 1695 km flood control/regulating structures and 4,310 km of drainage canals have been constructed by the Bangladesh Water Development Board. Existing Embankment in Bangladesh has shown in figure 3.7.

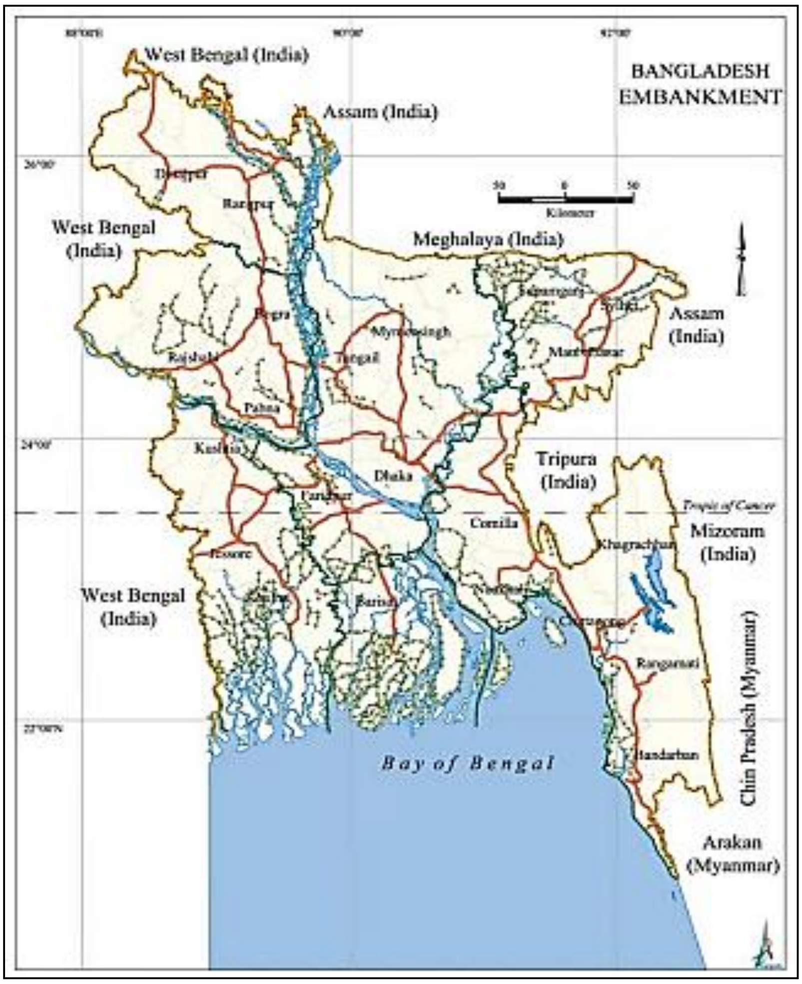

Figure 3.7: Existing Embankment in Bangladesh (Source: Banglapedia, National Encyclopedia of Bangladesh)

Embankments and polders have reduced floodplain storage capacity during floods, leading to an increase in water levels and discharges in many rivers (Chowdhury, 1998). Earthen embankment forms the primary structural element of flood control, drainage and irrigation projects in Bangladesh. Embankments has constructed using soil available at the site of construction. Most of the flood embankments have been constructed by BWDB. Some general geometric design parameters of embankments are presented in table 3.2.

Table 3.2: Geometric design parameters of embankments (Source: BWDB, 1996; BCL and Halcrow, 1988; Kampsax International A/S and Others, 1992)

Embankment type	Geometric parameters			
	River side slope	Country side slope	Free board (m)	Crest width (m)
Embankment along major rivers	1 : 3	1 : 3	1.5	4.3-7.3
Embankment along medium/ small rivers	1 : 2 to 3	1 : 2	0.9	2.5-4.3
Submersible embankments	1 : 3	1 : 3	0.3	2.5-4.3
Sea facing coastal embankment	1 : 7	1 : 2	1.50	4.3
Interior coastal dikes	1 : 3	1 : 2	0.9-1.50	4.3
Marginal coastal dikes	1 : 2	1 : 2	1.50	2.5

Along major rivers large areas are required for constructing embankments with base width of 27 to 40 meter. As per the Standard Design Manual of BWDB (1996), a design flood return period of 20 years is chosen in designing the embankment height where agricultural damage is predominant and that of 100 years is chosen where loss of human lives, properties and installations are predominant. In general, 1:100 year’s flood is considered for major rivers Jamuna, Padma and Meghna. For coastal embankments, 1:20 year floods are considered. Coastal embankments are designed to prevent tidal inundations. The minimum crest width is 2.50 m, and a minimum of 4.3 m is provided if the embankment is to be used as inspection roads. Larger widths are provided depending on the road structure if it is to be used as road. LGED also constructs flood embankments for very small projects. The embankment is provided with crest level of 1:20 year flood level plus 0.6 m freeboard (minor rivers) or 1.0 m freeboard (medium rivers), countryside slope and riverside slopes of 1:1.5 to 3 depending on the soil condition, minimum crest width of 3 m and 4 m if vehicles are to be allowed as per the Design Manual of LGED (1990) (Chowdhury, 1997).

Dredging of Rivers and canals

Dredging is done to increase discharge capacity of rivers and canals. Loop cuts are applied for highly meandering river through excavation of pilot channels. Due to high cost, limited dredging is done at critical locations like off-takes and confluences to remove sand bars for drainage improvement. Manual digging of canals is being practiced under the Food-For-Work (FFW) programs and is an important source of employment for the rural people.

Dredging represents the removal of material from the bed of the river deepening it. Channel cross-section is increased so the river can hold greater discharge due to dredging shown in figure 3.8. It can also represent a modified channel cross section. It looks more natural because no structures are built. By enlarging the cross-sectional area and increasing the bankfull discharge of the river along with its hydraulic radius. This has increased the velocity of the river and reduce the chances of it flooding in the immediate area by moving the floodwater further on downstream.

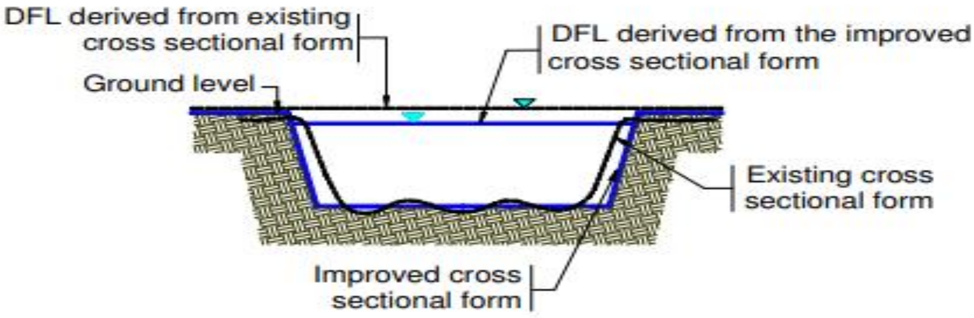

Figure 3.8: Dredging of river applied to increase the river flow capacity

Sometimes combination of embankment and dredging have provided together shown in figure 3.9 for flood mitigation.

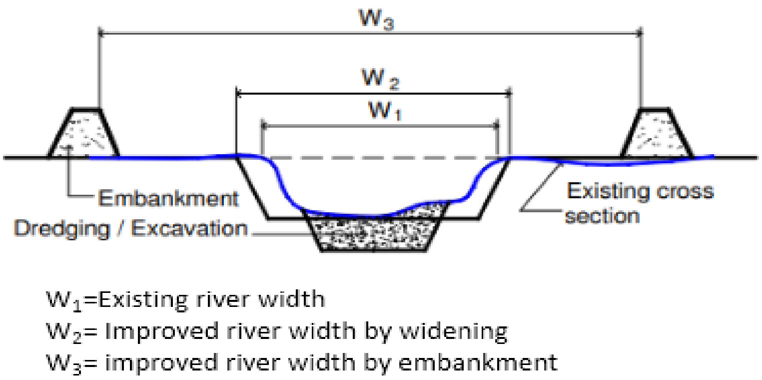

Figure 3.9: Combination of embankment and dredging to increase the river flow capacity

Flow Regulating Structures

Drainage regulators and sluices have been incorporated with the embankments in most of the cases to effect drainage of water from the land behind the embankment or from within the poldered area by gravity flow. Drainage regulators in the non-tidal areas are constructed considering 10-day rainfall with 1:10 year return period and 1:10 year peak river stage for effective drainage in the pre-monsoon season and 1:10 year rainfall and 1:10 year 10-day average water level for effective drainage in the post-monsoon season (BWDB, 1996). The structural stability is analyzed on the basis of 1:25 year pre-monsoon storm. Flushing regulators are provided in submersible embankments in the haor areas to fill the protected area in the monsoon to such a level that allows overtopping of embankments at safe hydraulic head. In the coastal polders, sluice gates are used to take advantage of tidal river fluctuations. Tidal drainage sluices are used with lowest possible crest levels and flap gates at the river outfall. These are sometimes used also as inlet structures (Chowdhury, 1997).

Channelization

Channelization projects are undertaken in order to increase flow depths for navigation and reduce flooding, by increasing the overall conveyance capacity, reducing friction and confining the flows into one single channel. This can be accomplished by straightening, widening, deepening, realigning and riveting the channel. Large wood pieces embedded in the river bottom caused localized backwater that leads to sediment accumulation, bar creation and subsequent vegetative growth. Removal of such material considerably changes water flow and sediment deposition patterns and is used as a channelization technique (WMO, 2003).

Bank protection and river training works

In general, the bank protection works practiced in Bangladesh may be classified into two types: (i) soft recurrent measures or active floodplain management (AFPM), and (ii) hard measures.

Soft recurrent measures: These are indigenous measures that intervene in the active floodplain by diverting the flow away from the reaches threatened by bank erosion and outflanking river channels. The following soft recurrent measures have been traditionally employed in Bangladesh: Surface (floating) screens widely used in the form of 'bamboo bandals' in the Jamuna River and in other similar types of rivers. These are the cheapest and have been found effective in the offtake of an outflanking channel. Bottom (fixed) screens along river banks below water extending from river beds. Recurrent revetments in the form of mattress composed of sand filled bags or tubes at outer banks. Permeable groynes made of bamboo and wooden poles used mainly on smaller and medium rivers, preferably at bifurcations. Sills made of bags, tubes or sand or a combination of the three i.e. a protected sand dyke, found effective at the outer channels. Artificial cutoffs for highly meandering small and medium rivers along very sharp bend by loop-cutting (excavating pilot channels).

Hard measures: These correspond to the classical approach to prevent river erosion and train the river in order to achieve a stabilized channel. The following hard measures have been employed in Bangladesh. - Flexible bank revetments and retaining structures for medium rivers. Brick mattressing, concrete blocks and boulder pitching for medium and major rivers. Impermeable groynes built on smaller as well as large rivers (Ganges, Jamuna, Lower Meghna, Teesta). Porcupines (bamboo crates filled with clay bricks) in smaller silt laden rivers. These are being used as emergency measures. Closure dams for redirecting river water flow in some desired direction.

3.4.2 Non-structural measurements

Non-structural Approach to Flood Mitigation

The Flood Forecasting and Warning Centre (FFWC) of BWDB, established in 1972, is responsible for making flood forecasts and flood warning during the flood season. The monitoring of floods and issue of flood forecasts are carried out in relation to Danger Levels (above which it is likely that the flood may cause damage to crops and homesteads) specified for each river gauging stations. The FFWC collects real-time data of water level (3 hourly) from 55 observation stations and rainfall from 54 observation stations which are transmitted through 61 Single Side Board Wireless stations and 14 Telemetric stations. Currently a hydrodynamic mathematical model (MIKE-11) is used to forecast water levels. At present, the FFWC issues river stages forecast for 21 stations on major and medium rivers where slowly rising floods occur, formulated for lead time of 24 hours, 48 hours and 72 hours with different ranges of accuracy. The forecasts in the form of daily water level bulletins are transmitted to national radio, television, news agencies, newspapers, concerned ministries and government offices and field wireless stations.

Flood preparedness

In Bangladesh, there is an institutional arrangement for flood preparedness under a National guideline entitled 'Emergency Standing Order for Flood'. It outlines the actions of flood preparedness to be taken up by a large number of Ministries (Ministries of Relief and Rehabilitation, Water Resources, Agriculture, Information, Health, Public Works, Local Government, Communication and Defense), subordinate agencies, local councils and NGO's in the three defined phases viz. before, during and after the flood. The overall flood management programs are coordinated by a National Coordination Committee. The recently formed Disaster Management Bureau of the Ministry of Relief and Rehabilitation is entrusted with the task of executing action programs at the grass root level. Around 20,000 volunteers of Bangladesh Red Crescent Society take part in the flood preparedness program in the storm surge flood prone area in the coastal region.

Flood Proofing

Flood proofing of homestead is a tradition of the rural settlements in Bangladesh. It is a combination of long-term, nonstructural and minor structural measures, as well as emergency actions, is important not only in reducing damage due to flooding, but also in preventing the negative impacts on the environment such as the spread of pollutants. It includes provision of quick drainage facilities such as the cleaning of primary and secondary drainage channels and clogged cross-drainage works before the onset of the flooding season. Homesteads are generally raised above unusual flood level. Ponds are dug in the homestead area and banks are raised to prevent intrusion of flood water. They are the source of domestic water supply. They are also used for fish culture and for conservation of water for irrigation during droughts. As per BNBC, any area having a potential for being flooded under at least 1m deep water due to flooding should be delineated as Flood Prone Area (FPA). The Code specifies that the lowest floor including the basement of any building located in the FPA shall not be located below the design flood level, and the roof of one or two storied buildings and the floor immediately above the design flood level for three or more storied buildings shall be accessible with an exterior stair.

Flood Plain Zoning

Flood zone describes that land area in terms of its risk of flooding. It is a procedure used to identify areas of varying flood hazard and has been used extensively as a precursor to land use regulation, a non-structural floodplain management. Flood plain zoning is a management strategy with the aim of reducing flood plain development. Flood plain zoning suggests that flood plains are divided into several zones. In zone one, no further development is allowed, apart from that in essential waterfront facilities. In the second zone, essential development is permitted.

Flood Fighting

Actions undertaken during floods to prevent damage and failure of flood control structures are known flood fighting. Flood fighting involves both collective and individual action. Flood fighting is an emergency measure of mitigating flood impacts on society and environment, particularly when flood control structures have proved ineffective or failed.

Floodplain Inundation Mapping

Floodplain inundation is a non-structural measure of flood mitigation. Flood inundation maps show the extent of flooding expected spatially over a given area. An easily accessible map graphics has provided users more awareness of the flood hazards in their local community. Combined with river observations and weather forecasts, inundation maps have provided decision makers additional information needed to mitigate the impacts of flooding and build more resilient communities.

Flood Shelter: Schools or health centers built on high mounds serve as flood shelters where flood vulnerable people can take refuge.

Cyclone Shelter: Cyclone shelters are constructed in the coastal zone where human lives are at high risk due to cyclonic storm surge floods. Currently there are around 1500 cyclone shelters. Multipurpose Cyclone Shelter Master Plan estimated that 2500 new shelters with a capacity of 4.4 million persons would be required. Over the years, there has been a significant change of emphasis from designing the shelters for single purpose use as flood shelter to design them for multipurpose use. Shelters are now designed as schools, health centers and other community service centers during normal life.

Flood Insurance

Spreading the costs of flood damages is mainly responsible to manage the damaging cost of affected people living in the society. Whereas other tools reduce the cost of flood damage from each flood, insurance distributes the losses over time and space. Flood insurance is presently available in many countries with well-developed insurance markets.

3.5 HEC-RAS

HEC-RAS is a computer program that models the hydraulics of water flow through natural rivers and other channels. 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 since its public release in 1995. Before the recent update to Version 5.0, 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 flow. The release of version 5.0 introduced two-dimensional modeling of flow as well as sediment transfer modeling capabilities. Besides, it is also capable of performing one- and two-dimensional hydraulic calculations for a full network of natural and constructed channels.

3.6 Capabilities of HEC-RAS

HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The following is a description of the major capabilities of HEC-RAS.

3.6.1 User Interface

The user interacts with HEC-RAS through a graphical user interface (GUI). The main focus in the design of the interface was to make it easy to use the software, while still maintaining a high level of efficiency for the user. The interface provides for the following functions:

• File management

• Data entry and editing

• River analyses

• Tabulation and graphical displays of input and output data

• Reporting facilities

• On-line help

3.6.2 Hydraulic Analysis Components

Steady Flow Water Surface Profiles

This component of the modeling system is intended for calculating 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 subcritical, supercritical, and mixed flow regime 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. The momentum equation is utilized 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). The effects of various obstructions such as bridges, culverts, dams, weirs, and other structures in the flood plain may be considered in the computations. The steady flow system is designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. Also, capabilities are available for assessing the change in water surface profiles due to channel modifications, and levees. Special features of the steady flow component include: multiple plan analyses; multiple profile computations; multiple bridge or culvert opening analysis; bridge scour analysis; split flow optimization; and stable channel design and analysis.

Unsteady Flow Simulation

This component of the HEC-RAS modeling system is capable of simulating one-dimensional unsteady flow through a full network of open channels. The unsteady flow equation solver was adapted from Dr. Robert L. Barkau's UNET model. The unsteady flow component was developed primarily for subcritical flow regime calculations. The 2D unsteady flow equation solver was developed at HEC and was directly integrated into the HEC-RAS Unsteady flow engine in order to facilitate combined 1D and 2D hydrodynamic modeling. The hydraulic calculations for cross-sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow module. Special features of the unsteady flow component include: Dam break analysis; levee breaching and overtopping; Pumping stations; navigation dam operations; and pressurized pipe systems.

3.6.3 Data Storage and Management

Data storage is accomplished through the use of "flat" files (ASCII and binary), as well as the HEC-DSS. 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. Data can be transferred between HEC-RAS and other programs by utilizing the HEC-DSS. Data management is accomplished through the user interface. The modeler is requested to enter a single filename for the project being developed. Once the project file name 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.

3.6.4 Graphics and Reporting

Graphics include X-Y plots of the river system schematic, cross-sections, profiles, rating curves, hydrographs, and inundation mapping. A three-dimensional plot of multiple cross-sections is also provided. Tabular output is available. Users can select from predefined 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.

How to Perform an Analysis

- Starting a New Project
- Entering Geometric Data
- Entering Steady Flow data
- Performing the Hydraulic Calculation
- Viewing Results
- Printing Graphics and Tables
- Exiting the Program

Performing a Steady Flow Analysis

• Entering and Editing Steady Flow Data
• Performing Steady Flow Calculations

Performing an Unsteady Flow Analysis

• Entering and Editing Unsteady Flow Data
• Performing Unsteady Flow Calculations
• Calibration of Unsteady Flow Models
• Model Accuracy, Stability, and Sensitivity

Viewing Results

After the model has finished the steady or unsteady flow computations the user can begin to view the output. Output is available in a graphical and tabular format. The current version of the program allows the user to view cross sections, water surface profiles, general profiles, rating curves, hydrographs, X-Y-Z perspective plots, detailed tabular output at a single location, and summary tabular output at many cross sections. Users also have the ability to develop their own output tables.

Contents

• Cross Section, Profiles and Rating Curves
• X-Y-Z Perspective Plots
• Tabular Output
• Viewing Results from the River System Schematic
• Stage and Flow Hydrographs
• Viewing Computational Level Output for Unsteady Flow
• Viewing Ice Information
• Viewing Data Contained in an HEC-DSS File
• Exporting Results to HEC-DSS

3.6.5 RAS Mapper

HEC-RAS has the capability to perform inundation mapping of water surface profile results directly from HEC-RAS. Using the HEC-RAS geometry and computed water surface profiles, inundation depth and floodplain boundary datasets are created through 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, you must have a terrain model in the binary raster floating-point format (.flt). The resultant depth grid is stored in the (.flt) format while the boundary dataset is store in ESRI's Shape file format for use with geospatial software.

3.7 Theoretical Basis for Hydrodynamic Calculation in HEC-RAS

3.7.1 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, applications of the momentum equation.

3.8 Theoretical Basis for One Dimensional and Two-Dimensional Hydrodynamic Calculation

Equations for Basic Profile Calculations

Water 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 called the standard step method. The Energy equation is written as follows

$$Z_2 + Y_2 + \frac{\alpha_2 V_2{}^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1{}^2}{2g} + h_e \quad \text{...} \quad (3.1)$$

Where,

Z_1, Z_2 = elevation of the main channel inverts
Y_1, Y_2 = depth of water at cross sections
V_1, V_2 = average velocities (total discharge/ total flow area)
α_1, α_2 = velocity weighting coefficients
g = gravitational acceleration
h_e = energy head loss
A diagram showing the terms of the energy equation is shown in figure 3.10.

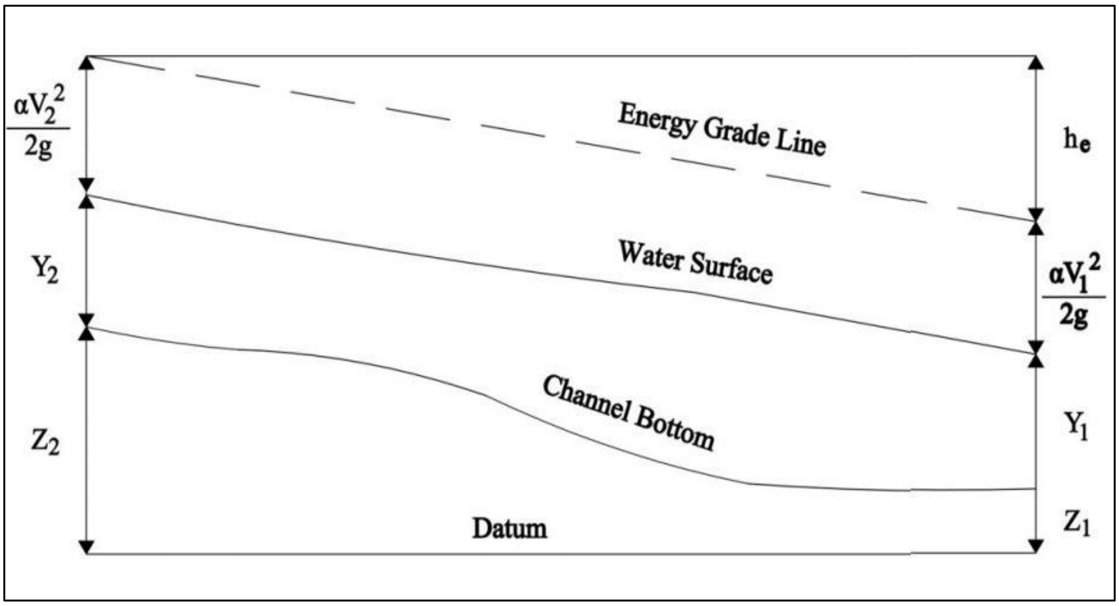

Figure 3.10: Representation of terms in the energy equation

The energy head loss (*he*) is expressed as

$$h_e = L\bar{S}_f + C\left|\frac{a_2V_2^2}{2g} - \frac{a_1V_1^2}{2g}\right| \qquad \text{..} (3.2)$$

Where,

L = discharge weighted reach length

S_f= representative friction slope between two sections

C = expansion or contraction loss coefficient

The distance weighted reach length, L, is calculated as:

$$L = \frac{L_{lob}\bar{Q}_{lob}+L_{ch}\bar{Q}_{ch}+L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob}+\bar{Q}_{ch}+\bar{Q}_{rob}} \qquad \text{..} (3.3)$$

Where,

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

Q_{lob} + Q_{ch} + Q_{rob} = arithmetic average of the flows between sections for the 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 gradually varied flow situations, and 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 an answer. The momentum equation is derived from Newton's second law of motion:

$$\sum F_x = ma \quad \text{(3.4)}$$

Force = Mass x Acceleration (change in momentum)

Applying Newton's second law of motion to a body of water enclosed by two cross sections at locations 1 and 2 (Figure 3.11) the following expression for the change in momentum over a unit time can be written:

$$\mathrm{P_2 - P_2 + W_x - F_f = Q\rho\Delta V_x} \quad \text{(3.5)}$$

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

ρ= Density of water

ΔV_x= Change on velocity from 2 to 1, in the X direction.

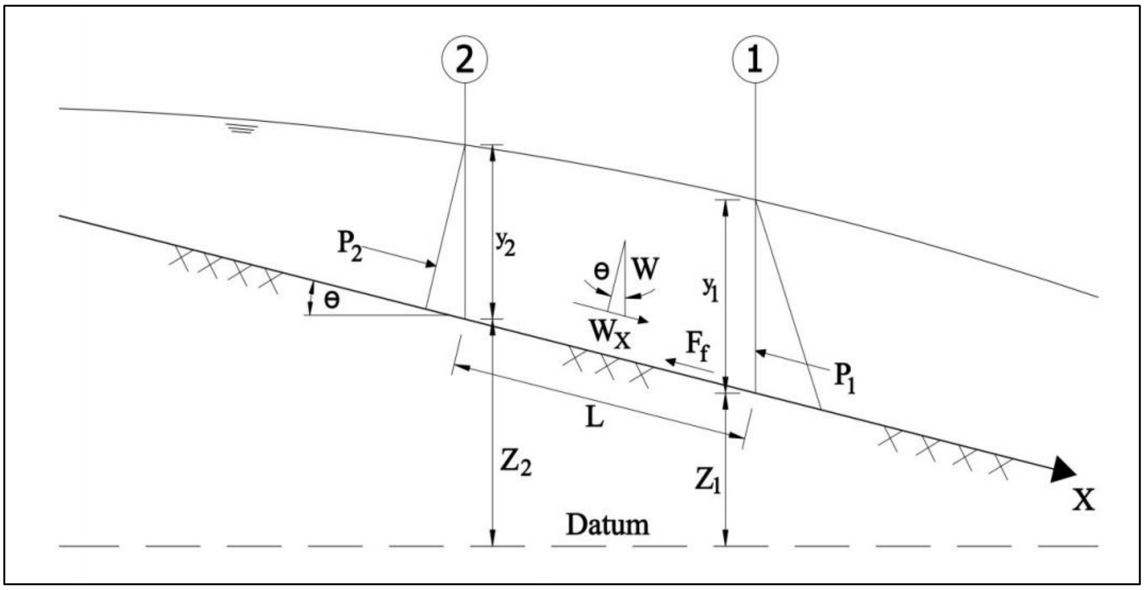

Figure 3.11: Application of Momentum Principle

The force in the X direction due to hydrostatic pressure is:

$$P = \gamma A\bar{Y}cos\theta \qquad (3.6)$$

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 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:

$$P_1 = \gamma A_1\bar{Y_1} \qquad (3.7)$$

$$P_2 = \gamma A_2\bar{Y_2} \qquad (3.8)$$

Where,

γ= unit weight of water

A_i= Wetted area of the cross section at locations 1 and 2

Y_i= 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)

$$W = \gamma\left(\frac{A_1 + A_2}{2}\right)L \qquad \text{(3.9)}$$

$$W_x = W \times \sin\theta \qquad \text{(3.10)}$$

$$\sin\theta = \frac{z_2 - z_1}{L} = S_0 \qquad \text{(3.11)}$$

$$W_x = \gamma\left(\frac{A_1 + A_2}{2}\right)LS_0 \qquad \text{(3.12)}$$

Where,

L= Distance between sections 1 and 2 along the X axis

S_0= Slope of the channel, based on mean bed elevations

z_i= Mean bed elevation at locations 1 and 2

Force to External Friction is:

$$F_f = \tau\bar{P}L \qquad \text{(3.13)}$$

Where,

τ = Shear Stress

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

$$\tau = \gamma\bar{R}\bar{S}_f \qquad \text{(3.14)}$$

Where,

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

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

$$F_f = \gamma\frac{\bar{A}}{\bar{P}}\bar{S}_f L \qquad \text{(3.15)}$$

$$F_f = \gamma\left(\frac{A_1 + A_2}{2}\right)\bar{S}_f L \qquad \text{(3.16)}$$

Mass time acceleration is

$$ma = Q\rho\Delta V_x \qquad \text{(3.17)}$$

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

$$ma = \frac{Q\gamma}{g}(\beta_1 V_1 - \beta_2 V_2) \quad \text{...} (3.18)$$

Where,

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

Substituting back into equation 3.5 and assuming Q can vary from 2 to 1

$$\gamma A_2 \bar{Y}_2 - \gamma A_1 \bar{Y}_1 + \gamma \left(\frac{A_1 + A_2}{2}\right) LS_o - \gamma \left(\frac{A_1 + A_2}{2}\right) L\bar{S}_f = \frac{Q_1 \gamma}{g} \beta_1 V_1 - \frac{Q_2 \gamma}{g} \beta_2 V_2 \quad \text{..........} (3.19)$$

$$\frac{Q_2 \beta_2 V_2}{g} + A_2 \bar{Y}_2 + \left(\frac{A_1 + A_2}{2}\right) LS_o - \left(\frac{A_1 + A_2}{2}\right) L\bar{S}_f = \frac{Q_1 \beta_1 V_1}{g} + A_1 \bar{Y}_1 \quad \text{.....................} (3.20)$$

$$\frac{{Q_2}^2 \beta_2}{g A_2} + A_2 \bar{Y}_2 + \left(\frac{A_1 + A_2}{2}\right) LS_o - \left(\frac{A_1 + A_2}{2}\right) L\bar{S}_f = \frac{{Q_1}^2 \beta_1}{g A_1} + A_1 \bar{Y}_1 \quad \text{.......................} (3.21)$$

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.

3.8.1 1D/2D coupled Hydraulic Modelling

This study is focused on the development of 1D/2D coupled hydrodynamic modeling for the Ghaghat River floodplain through HEC-RAS 5.0.1 published by USACE. The equations for 1D/2D coupled modeling have been stated in (Patel et al., 2017). The HEC-RAS 5.0.1 is fully solved in using the 2D Saint-Venant equation (Brunner 2016b; Manual 2016; Quirogaa et al., 2016):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial x} = 0 \quad \text{..} (3.22)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -\frac{n^2 pg\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \xi}{\partial x} + pf + \frac{\partial}{\rho \partial x}(h\tau_{xx}) + \frac{\partial}{\rho \partial y} h\tau_{xy} \quad \text{....} (3.23)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -\frac{n^2 qg\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \xi}{\partial y} + qf + \frac{\partial}{\rho \partial y}(h\tau_{yy}) + \frac{\partial}{\rho \partial y} h\tau_{xy} \quad \text{...} (3.24)$$

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

3.9 Geographic Information System

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 perform 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 GIS 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 constructs.

3.9.1 Data Model

Geographic elements in a GIS are typically described by two data models: vector and raster. Each of these is described below:

Vector

Vector objects include three types of elements: points, lines, and polygons. 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, 1999). 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. Each cell is assigned a numerical value that defines the condition of any desired spatially varied quantity (Smith, 1999). 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).

3.10 Summary

Theoretical background of a model plays a vital role in any research study. Without having the knowledge of theoretical background, it is quite tough to analyses the results and predicts the scenario from simulation of a model. It is also essential to know about the background equation on which the theory based on. If the concepts of theoretical background are clear, then the utilization of model can be done properly. In this chapter theoretical background and equation of model have been studied and reviewed.

CHAPTER 4
METHODOLOGY

4.1 General

Flood Inundation Mapping helps the communities to visualize potential flooding scenarios, identify areas and resources that may be at risk, and enhance their local response effort during a flooding event. The estimation of the flood depth, the extents of flooded area are essential in a flood-prone area for flood control and protection. This chapter describes a brief discussion about the methodology to achieve objectives of the study.

4.2 Data Collection

In order to develop the mathematical flood model, various kinds of data, recent and previous years have been collected and compiled. According to the modeling requirements, a significant amount of data includes water level, discharge, cross-section have been collected and setup flood model using this data. All collected data are summarized in the table 4.1.

Table 4.1: Summary of data collection

Data Type	Data Source	Data Location	Periods (year)
Discharge Data	BWDB	Jafarganj Road Crossing (SW96A)	(1978-2017)
Water Level	BWDB	Jafarganj Road Crossing (SW96A), Islampur (SW96), Mirjapur (SW96.5) and Gaibandha (SW97)	(1978- 2019)
Cross Section	BWDB IWM	(RMGHT1- RMGHT12) (RMGHT13- RMGHT36)	(2004-2013)
SRTM DEM	USGS	Bangladesh	2015
Observed Flood Map	FFWC	Bangladesh	(1988-2017)
Satellite Image	MODIS/ USGS/ Earth Explorer	Bangladesh	(2004-2010)

These data also form the basis for further analysis and interpretation of the model results leading to accurate assessment of hydrological condition of Ghaghat River floodplain. A brief description of all the data used in the study is presented below.

4.2.1 Discharge Data

The flow hydrographs of the Ghaghat River at Jafarganj Road Crossing (SW96A) and Gaibandha (SW97) gauge station have been collected from the Bangladesh Water Development Board (BWDB) for the year 1978-2016. The hydrograph comprises of data at an interval of one day. Locations of this station where the historical water discharge data of Ghaghat River have been collected from BWDB is shown in figure 4.1.

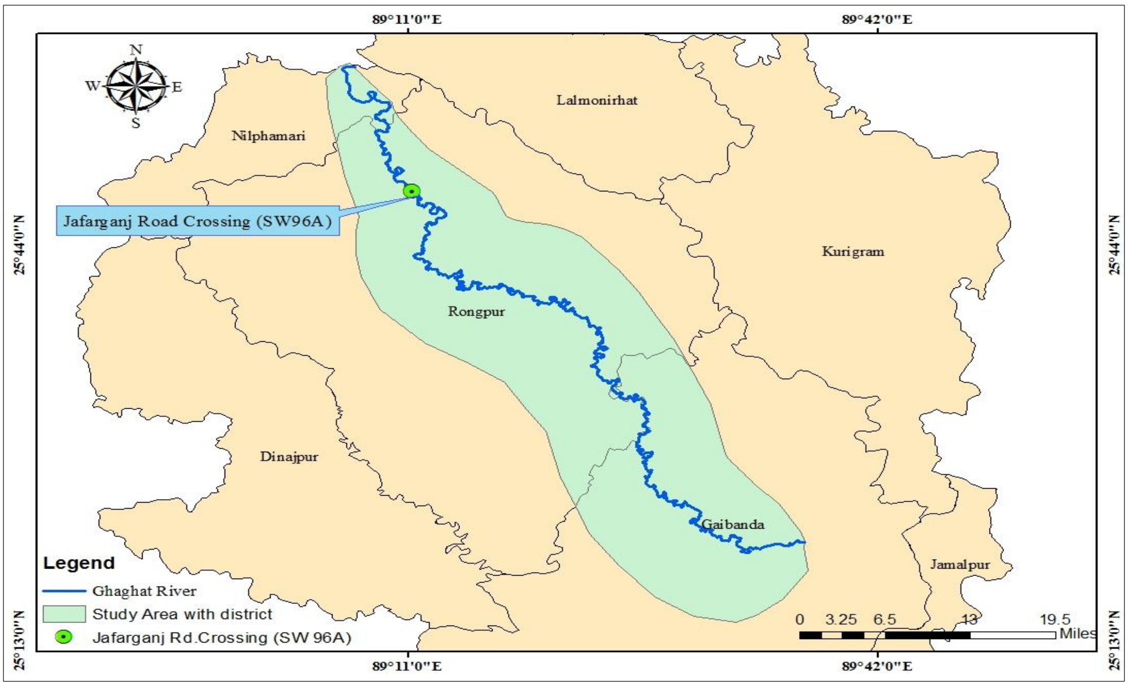

Figure 4.1: Locations of discharge station of Ghaghat River

The discharge data of Jafarganj Road Crossing (SW96A), has been used as the upstream boundary condition in the model.

4.2.2 Water Level Data

The stage hydrographs of the Ghaghat River at Jafarganj Road Crossing (SW96A), Islampur (SW96), Mirjapur (SW96.5) and Gaibandha (SW97) gauge station have been collected from the Bangladesh Water Development Board (BWDB) for the year 1978-2019. The hydrograph comprises of data at an interval of one day. The water level data of Gaibandha (SW97) has been used as the downstream boundary condition in the model. The data of year 2013 has been used to calibrate and the year of 2015 data has been used to validate the hydro-dynamic model. Locations of four stations where water level data of the Ghaghat River have been collected from BWDB are shown in figure 4.2.

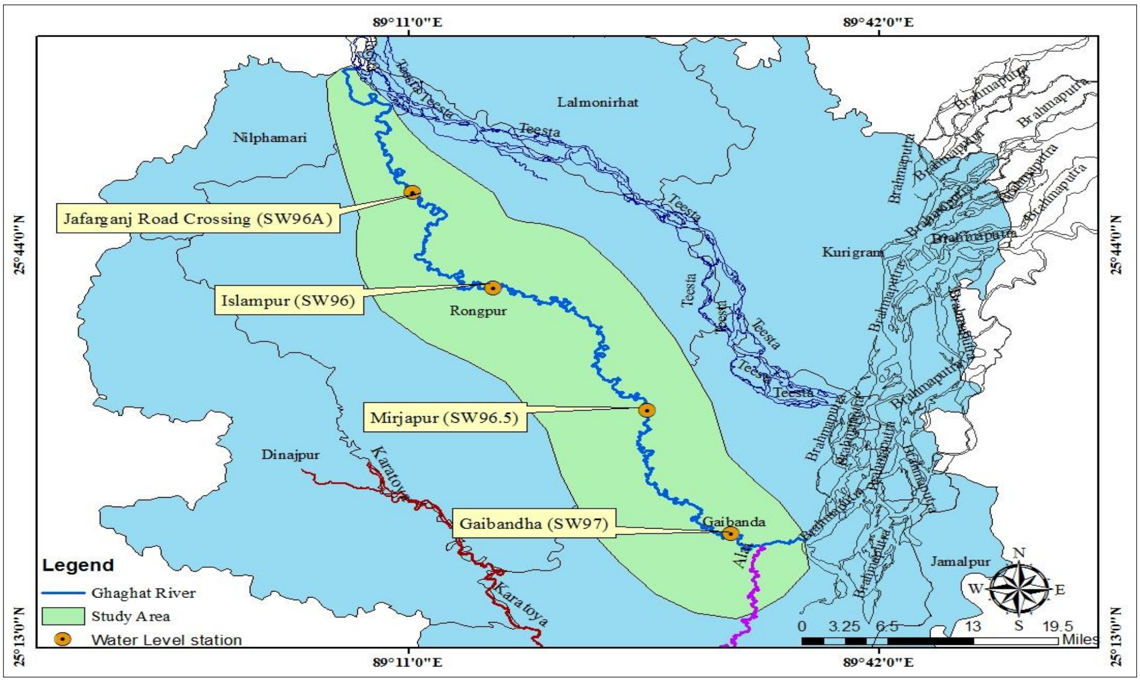

Figure 4.2: Locations of water level station of Ghaghat River

4.2.3 Cross-section

River cross-sections of Ghaghat River are collected for the years of 2004-2013 from Bangladesh Water Development Board (BWDB). BWDB collects cross-section data at 12 different stations of Ghaghat River designated by RMGHT1- RMGHT12 shown in figure 4.3. Cross-section data of RMGHT13- RMGHT36 has collected from Institute of Water Modeling. These cross-sections depict the shape and bathymetry of the rivers.

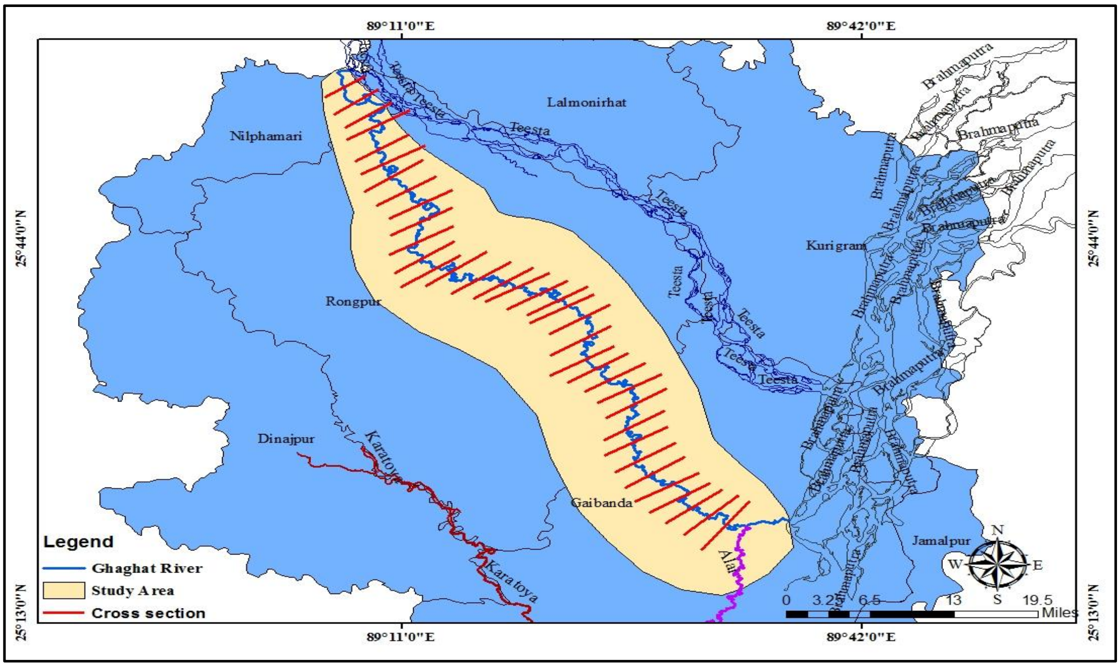

Figure 4.3: Locations of cross-section of Ghaghat River

4.2.4 Digital Elevation Model (DEM)

A digital elevation model (DEM) is a digital model or 3D representation of a terrain's surface, 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). DEMs are commonly built using data collected using remote sensing techniques, but they may also be built from land surveying. This data is required to formulate mathematical models for the study area. Each cell, and cell face, of the computational mesh of 2D flow area has 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 Shuttle Radar Topography Mission (SRTM) is a digital elevation model that uses radar technology to measure the elevation of the Earth's surface. The accuracy of SRTM data depends on several factors, including the resolution of the data, the processing techniques used, and the terrain being measured. In general, the accuracy of SRTM data is considered to be high, with vertical accuracy ranging from +/- 16 meters to +/- 10 meters. However, the accuracy may be lower in areas with dense vegetation, steep slopes, or other challenging terrain features. SRTM data remains a valuable resource for many applications, including mapping, hydrology, and land use planning.

This data has emerged as a global elevation data in the past one decade because of its free availability, homogeneity and consistent accuracy compared to other global elevation dataset. The present study explores the hydrological modeling with the help of digital elevation model (DEM) from SRTM. In this study 30m DEM (Digital Elevation Model) of Bangladesh in raster format has been collected from the FTP server of the Shuttle Radar Topographic Mission (SRTM) of National Aeronautics and Space Administration (NASA). Then this DEM has been cropped by the shape of study area. Later it has been modified to Bangladesh Traverse Mercator (BTM) with respect to mPWD datum. Figure 4.4 represents the Digital Elevation Model (DEM) of the study area.

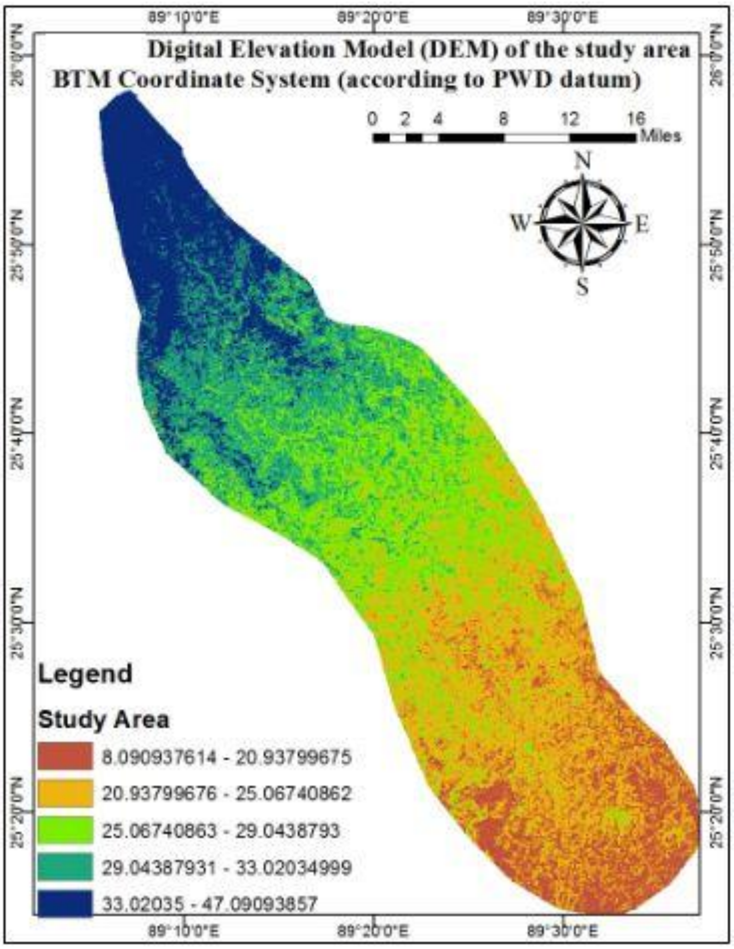

Figure 4.4: Digital Elevation Model (DEM) of the study area

4.2.5 Satellite Image

For the purpose of comparison between simulated flood map and observed flood map, Sentinel- 2 satellite images have been collected from United States Geological Survey (USGS)/Earth Explorer.

The Sentinel-2 satellites capture high-resolution multispectral images of the Earth's surface, with a revisit time of five days at the equator. The satellites are equipped with a high-resolution imaging instrument called the Multispectral Instrument (MSI), which captures 13 spectral bands ranging from visible to near-infrared. The MSI has a spatial resolution ranging from 10 to 60 meters, depending on the spectral band, and covers a swath width of 290 kilometers.

The Sentinel-2 images are used for a variety of applications, including land cover mapping, vegetation monitoring, crop management, disaster response, and water quality monitoring. The collected satellite images are of North-West (NW) region of Bangladesh of different year are to be used for the visualization of inundated area in these years. These images have been used for the comparison with the simulated flood map. Figure 4.5 represents the Satellite Image of the study area.

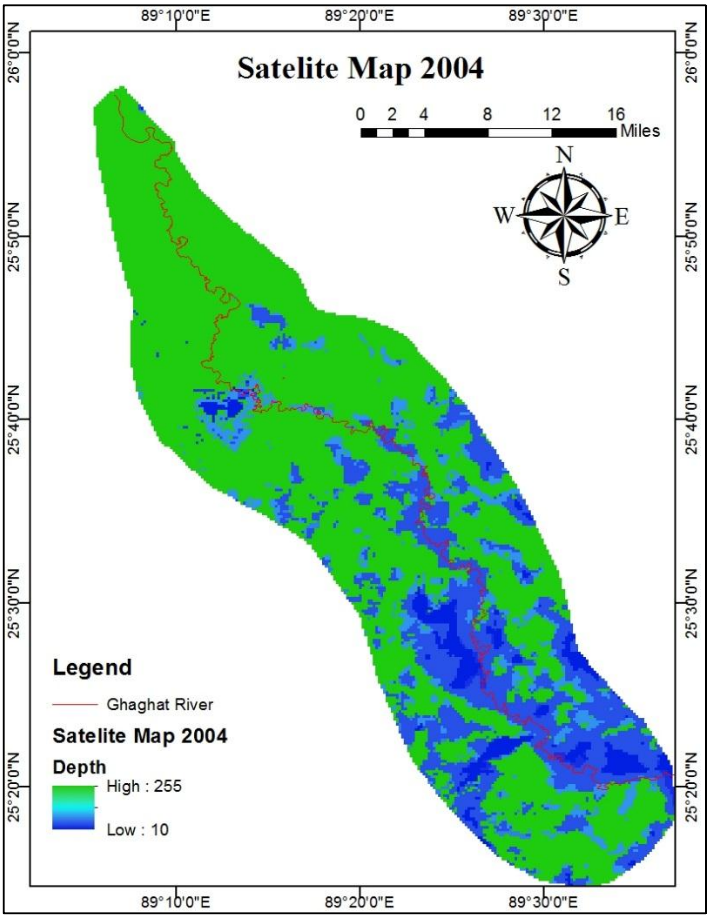

Figure 4.5: Satellite Image of the study area

4.3 Overview of Methodology

Modeling of any physical phenomenon become successful when practicing a process of an iterative development meaning. Model refinements are based on the availability and quality of data, hydrological understanding and scopes of the study. The general approach that has been followed in the current study can be summarized in the flow chart given in figure 4.6. To achieve the study objectives, a brief description of the methodology and approaches that are followed has been provided in this section.

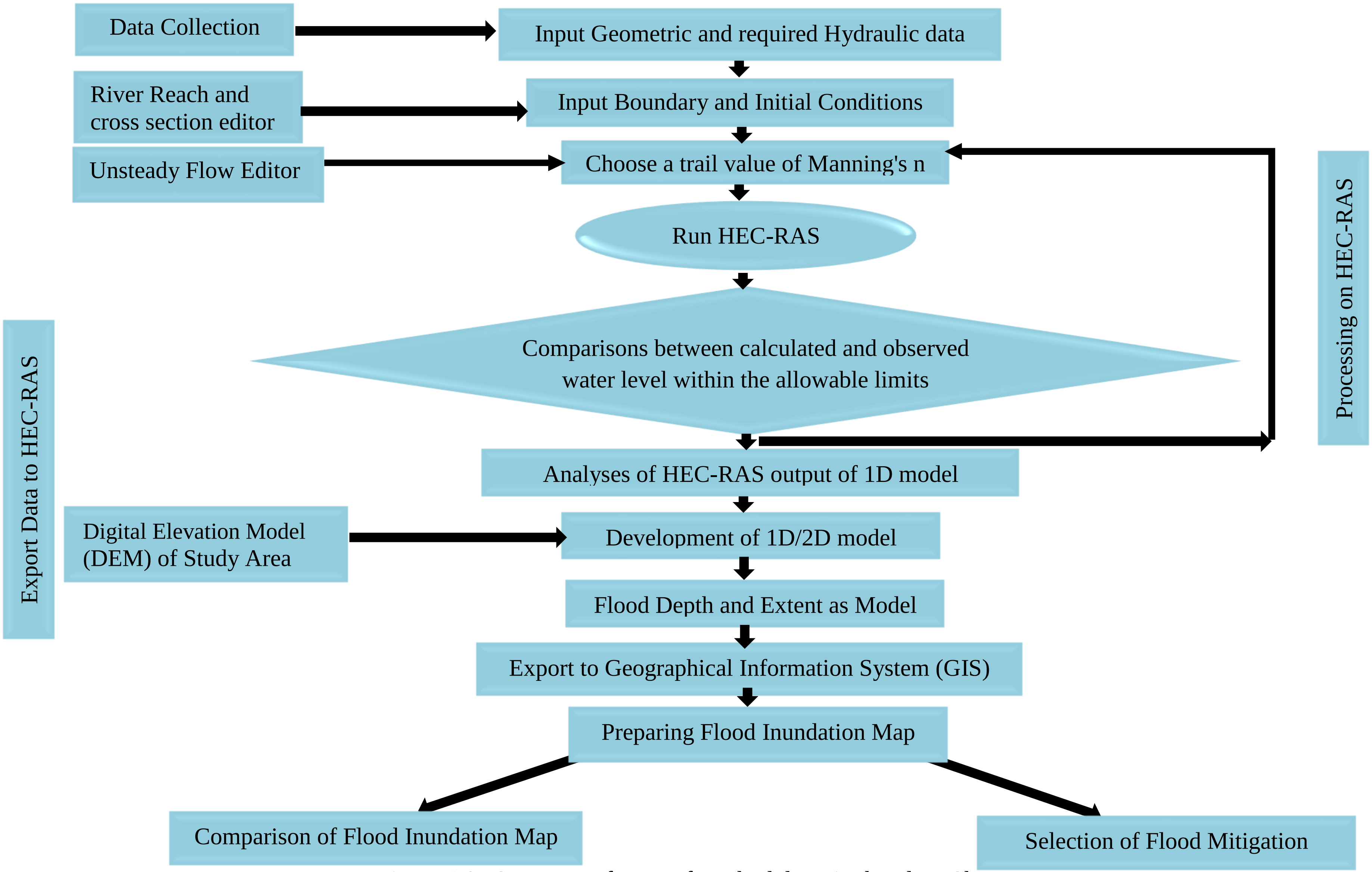

Figure 4.6 : Summary of steps of Methodology in the Flow Chart

4.4 Steps of HEC-RAS Model Setup

Few sequential steps have been followed to set up the HEC-RAS model, which are 1. HEC-RAS 1D model set up (considering boundary condition for 1D model), 2. processing of DEM for HEC-RAS 1D-2D coupled model (includes datum correction of Digital Elevation Model (DEM), clipping of the study area from DEM, 3. HEC-RAS 1D-2D Coupled model (incorporation with 1D hydrodynamic model, developing a terrain model, 2D Flow area computational mesh, 1D-2D coupling through lateral structure, boundary conditions for 1D-2D model), 4. calibration and validation, 5. model performance evaluation, 6. Finally, preparation of flood inundation maps. The flow chart of model setup in HEC-RAS has been showed in figure 4.7

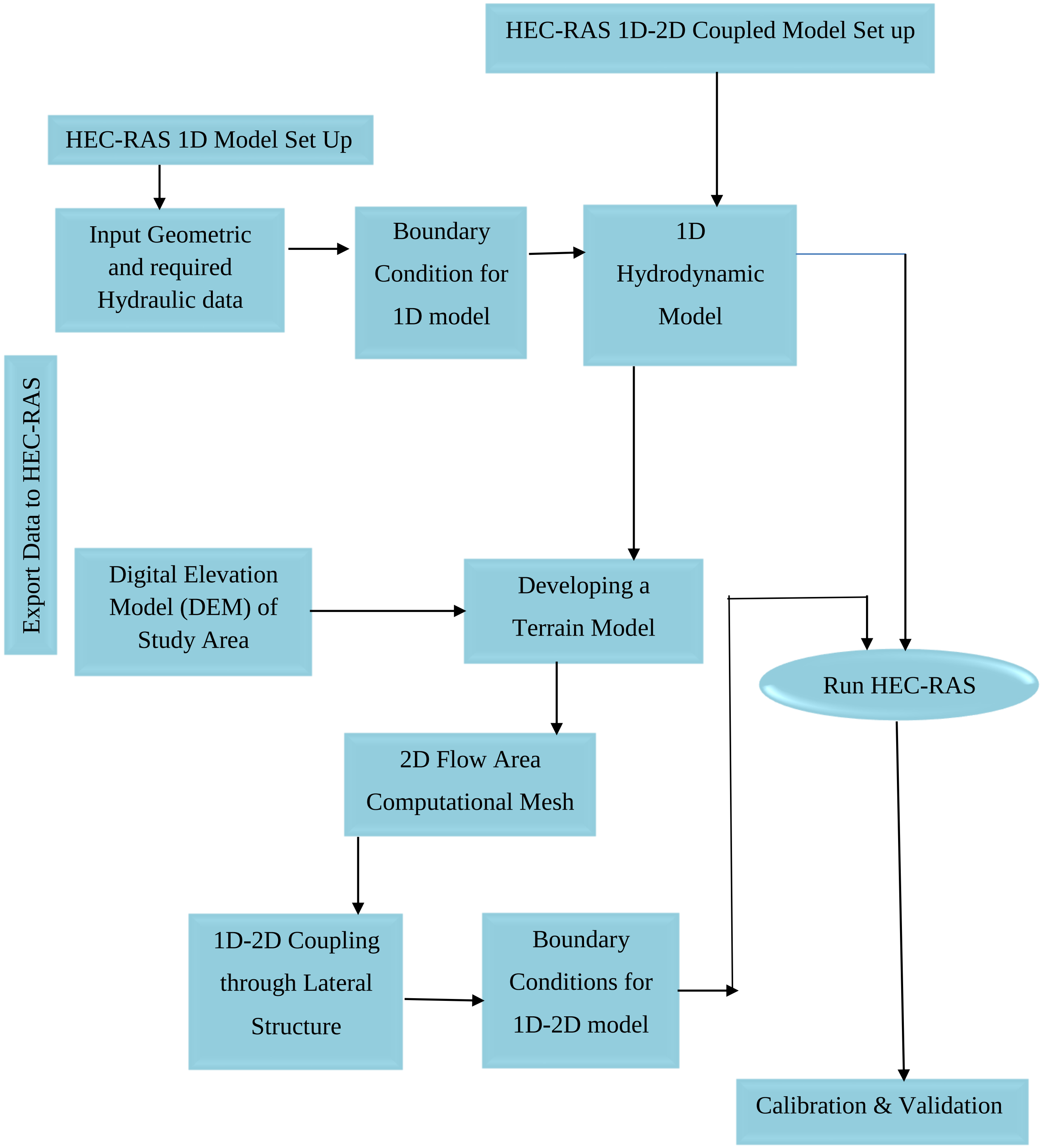

Figure 4.7: Flow Chart of Model Setup in HEC-RAS

4.5 Calibration of model

To simulate the model with base and different flow conditions, it is necessary to test the model's performance. Sets of field data are prerequisite for the testing. This testing provides an impression about the degree of the accuracy of the model in reproducing river 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, HEC-RAS 1D model has been calibrated for the year 2013. For this study, the Mirjapur (SW 96.5) station is used as the calibration point because it is the intermediate hydrologic station between Islampur and Gaibandha stations which shown in figure 4.8.

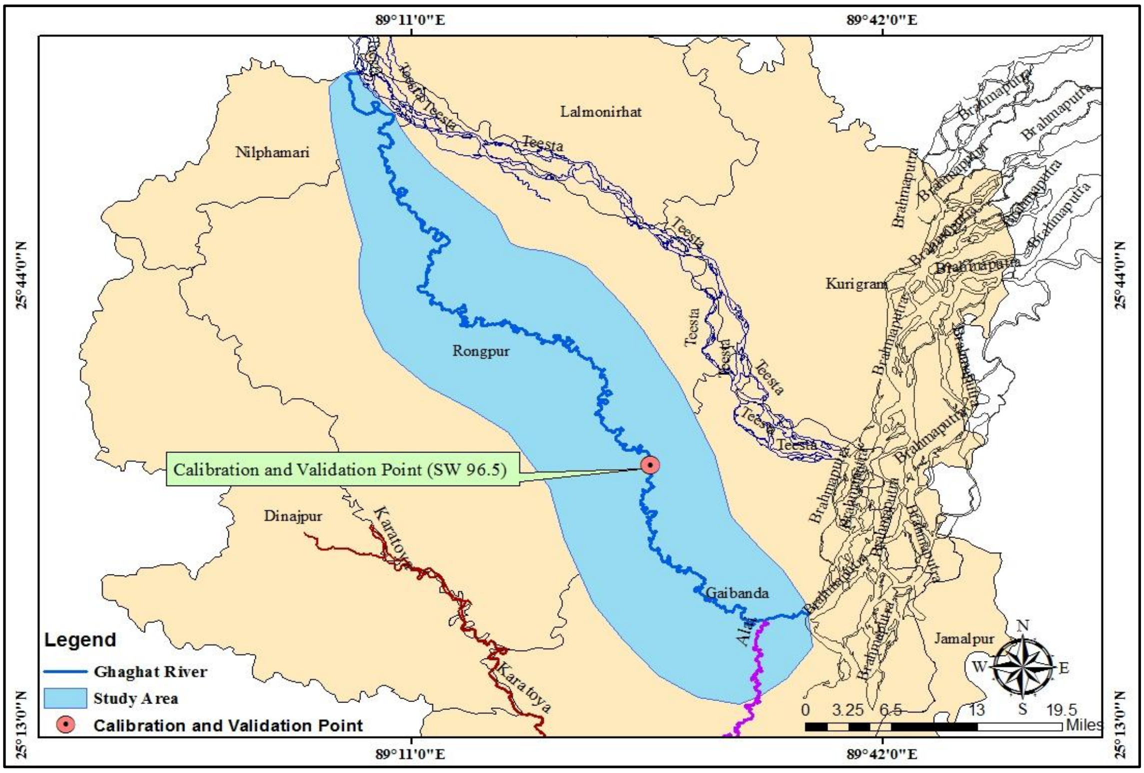

Figure 4.8: Location of Calibration and Validation of Model

4.6 Validation of model

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 has been used to validate the WL for the year 2015. For this study, the Mirjapur (SW

96.5) station is used as the validation point because it is the intermediate hydrologic station between Islampur and Gaibandha stations which shown in figure 4.8.

4.7 Performance Evaluation of Model

The quantitative statistics were divided into two 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.

Coefficient of determination (R^2)

Coefficient of determination (R^2) describes the degree of collinearity between simulated and measured data (Rahman, 2016). 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,

$$r = \frac{n\sum(xy-(\sum x)(\sum y))}{\sqrt{n(\sum x^2)-(\sum x)^2}\sqrt{n(\sum y^2)-(\sum y)^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

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

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 has computed as shown in equation 4.2.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{mean})^2}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

Where, Y_i^{obs} *is* the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y_i^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE =1 being the optimal value (Rahman, 2016). Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Gupta et al., 2009; Servat and Dezetter, 1991) also found NSE to be the best objective function for reflecting the overall fit of a hydrograph.

4.8 Comparison of Simulated and Observed Flood Inundation Map

After calibration and validation of one-dimensional HEC-RAS model, an attempt has been taken to develop a one dimensional and two-dimensional coupling model. It has done on purpose of 1D flow of water in the main channel and 2d flow of water in flood plain of Ghaghat River while water overflows its main channel banks. 1D and 2D run have showed inundation scenarios of flood that is important to check the flood delineation area and depth. In this section qualitative comparison among simulated map, satellite image and observed flood maps for 2004 and 2007 have been shown.

4.9 Flood Inundation Classification

The depth files are exported directly from RAS-Mapper. Later they are processed in ArcGIS. In this study, Inundation have classified into five classes: F0 (0-0.3 m), F1 (0.3 m- 0.9 m), F2 (0.9 m-1.8 m), F3 (1.8 m-3.6 m) and F4 (>3.6 m). This inundation classification is developed by the National Water Management Plan (NWMP). Later, this classification is used in many flood studies of Bangladesh (Tazin, 2018; Rouf, 2015; IWM, 2014).

4.10 Flood mitigation measures

Flood mitigation measure can be applied on the flood affected area which is identified by flood inundation map. It is necessary to mitigate the flood from this region which people experienced over the year. For the purpose of reducing the flood problem, various measures can be taken. For flood mitigation of Ghaghat River (i) embankment has provided both side of the river to protect the flood plain from inundation, (ii) dredging has executed in different portion to increase flow carrying capacity, (iii) combination of embankment and dredging has provided.

4.11 Identification of best measure

With calibrated and validated model, three options have been carried out for flood mitigation, which are

(i) Embankment

Embankment of suitable size, length and location can be set by different trial analyses which have been provided both side of Ghaghat River to protect the flood plain from inundation. In this scenario, existing embankment height has been raised from 0.5m to 1.25m as well as new embankment has been constructed from the ending location of existing embankment according to different simulation for reduction of percentage of flood inundation area.

(ii) Dredging

Dredging of different depth, distance and location can be set by different trial analyses has been executed in different portion to increase discharge carrying capacity for Ghaghat River. Dredging has been executed not only at downstream cross-section 2 to 9 of the river but also cross-section 15 to 22 nearest one-third length of the river at a depth of 0.5m to 1.5m from downstream for reduction of percentage of flood inundation area.

(iii) Combination of Embankment and Dredging

In this scenario, new embankment has been provided also height of existing embankment has raised at downstream. At the same time dredging section has been provided at cross section 15 to 22 for a depth of 0.5m to 1.5m for reduction of percentage of flood inundation area.

As a measure of flood mitigation, the scenario with the highest percentage reduction in flood inundation area has been chosen.

4.12 Summary

Methodology is the specific procedures or techniques used to identify, select, process, and analyze information about a topic. A qualitative methodology might be used to evaluate a study's aims, objectives, overall validity and reliability. This chapter represents a brief description of how the whole process has been continued. The data collection process based on methodology has been represented in this chapter. The detail process of Hec-Ras 1D model and Hec-Ras 1D/2D setup for Ghaghat River have been explained in this chapter. Qualitative comparison among simulated, satellite image with observed flood maps have been checked for visual calibration. For flood mitigation, different measures have taken in to account which has been represented in this chapter accordingly. Existing embankment height has been raised for both side of the river, construction of new embankment at both side of the river has been implemented for scenario 1. Dredging has been executed at downstream mid length of the river at a depth for scenario 2. Combination of scenario 1 and 2 has been established as scenario 3.

Further description and analysis based on this methodology has been discussed in the following chapter.

CHAPTER 5
DATA ANALYSIS AND MODEL SETUP

5.1 General

In this chapter the preprocessing of data for model setup and outcome of the development and analysis of hydrodynamic model has represented. After model setup and calibration/validation, analysis of model output has carried out in order to prepare flood inundation map as well as develop flood mitigation scenarios to minimize flood. The hydrodynamic model HEC-RAS selected for this study operates on computational time step and uses digital elevation data, water level, morphological data and river discharge. When the data is arranged in the required format, the model simulation takes a sufficiently high amount of time based on lateral structure connection of 1D cross section with 2D floodplain.

5.2 Hydrological Data Analysis

5.2.1 Discharge

The hydro-morphological characteristics of a river is the intricate components of a river system. This hydro-morphological condition of river depends on the position of the off-take and the deviation of flow direction to the off-take from the parent river.

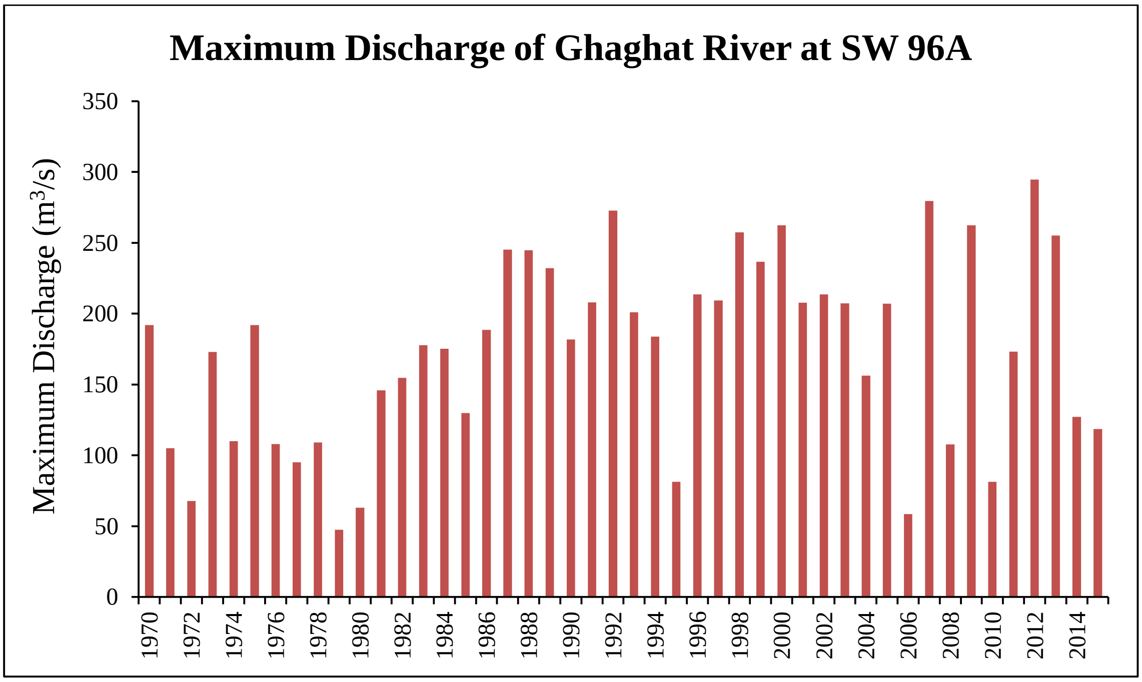

Figure 5.1: Peak annual discharge of Ghaghat at Jafarganj Road Crossing (SW 96A) for past years

Ghaghat River located on Ghaghat-Teesta Floodplain which covers the southeastern floodplain of the Ghaghat River and is terminated by northeastern Barind Tract. The pattern of meander scars, loop, scrolls and abandoned channels indicate a gradual shifting of the Ghaghat River towards SE direction. Few elongated and semi-circular flood basin or depressions having 1 to 8 km length and 1 to 2 km width are present in this unit. Sinuosity of the Ghaghat River increases abruptly towards south of the Kurigram District, which indicate an increase in flatness of topography.

Jafarganj is the only gauging station in Ghaghat River for which flow data is available for the period 1964-1980. The flow is measured weekly in the monsoon and fortnightly at times monthly during lean season. Daily mean flow is estimated from recorded mean water level with the help of rating curves. Annual maximum peak flow computed from rating curve is 361 m^3/sec. This station was discontinued from 1981 but restarted around 1988.

Analysis of annual maximum flow of Ghaghat at Jafarganj Road Crossing (SW 96A) from 1970 to 2014 as shown in figure 5.1 demonstrates that the flow trend is increasing as well as decreasing over the year.

The declining pattern indicates to some extent that the flow from the offtake of the Ghaghat has been declining due to siltation thus the carrying capacity of the river throughout the reach is also decreasing which in turn increases the tendency of flood in dry land during monsoon.

The annual flow of the river varies substantially as found from the data of 1970 to 2015 where the highest recorded discharge of the river at Jafarganj Road Crossing is 289m^3/s during monsoon in year of 2012 and the lowest recoded discharge was measured in 1979. Maximum discharge increases during 1981 to 1983 and decreases during 1984 to 1985 and this increasing and decreasing process repeated every time. Analysis on minimum flow of Ghaghat River at the same station showed that during the low flow season the discharge gets reduced to less than 10 m^3/s and has been found as low as 1m^3/s during specific dry period of a year (Noor, 2013).

5.2.2 Water level

Ghaghat River has four water level stations. All of them are water level data measuring stations surround the study area collected to conduct analysis in this study.

Figure 5.2 to figure 5.5 show the maximum, minimum and average water level of Ghaghat River at Jafarganj Road Crossing (SW96A), Islampur (SW96), Mirjapur (SW96.5) and Gaibandha (SW97) respectively.

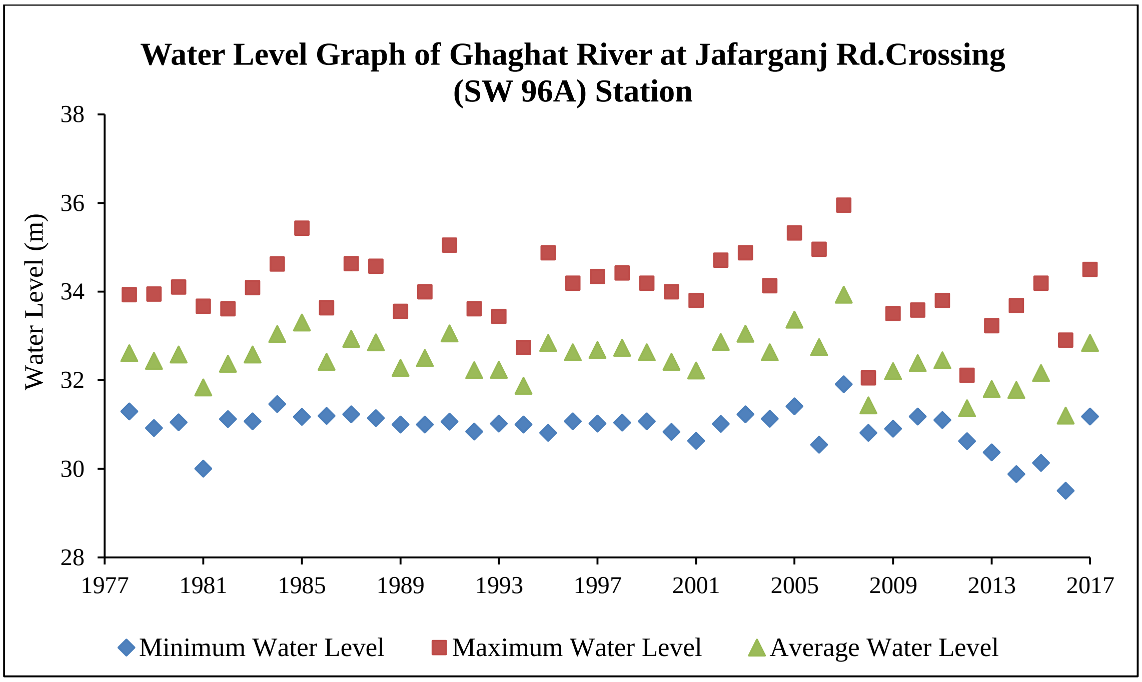

Figure 5.2: Water Level of Ghaghat River at Jafarganj Rd. Crossing (SW 96A) Station

At Jafarganj road crossing water level is slightly in increasing trend. The maximum water level of 35.95 meters occurred in 2007 and the minimum water level of 29.5 meters occurred in 2016.

At Islampur water level is in slight decreasing trend as well with maximum in 2007 and minimum in 2016. At Mirjapur water level is in slight increasing trend as well with maximum in 2005 and minimum in 2001.

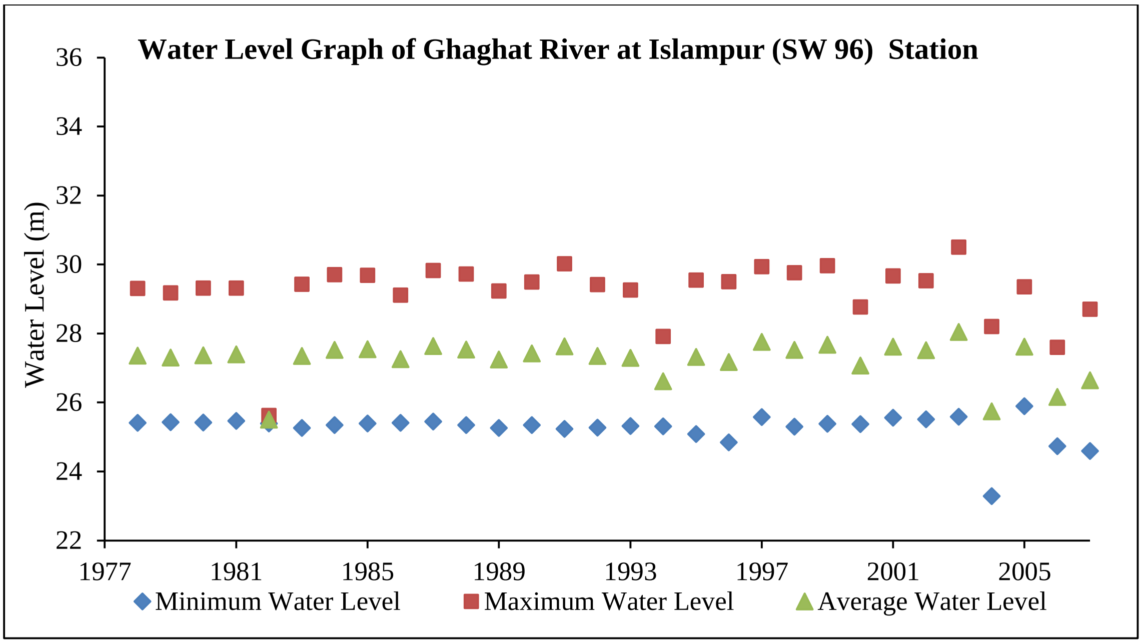

Figure 5.3: Water Level of Ghaghat River at Islampur (SW 96) Station

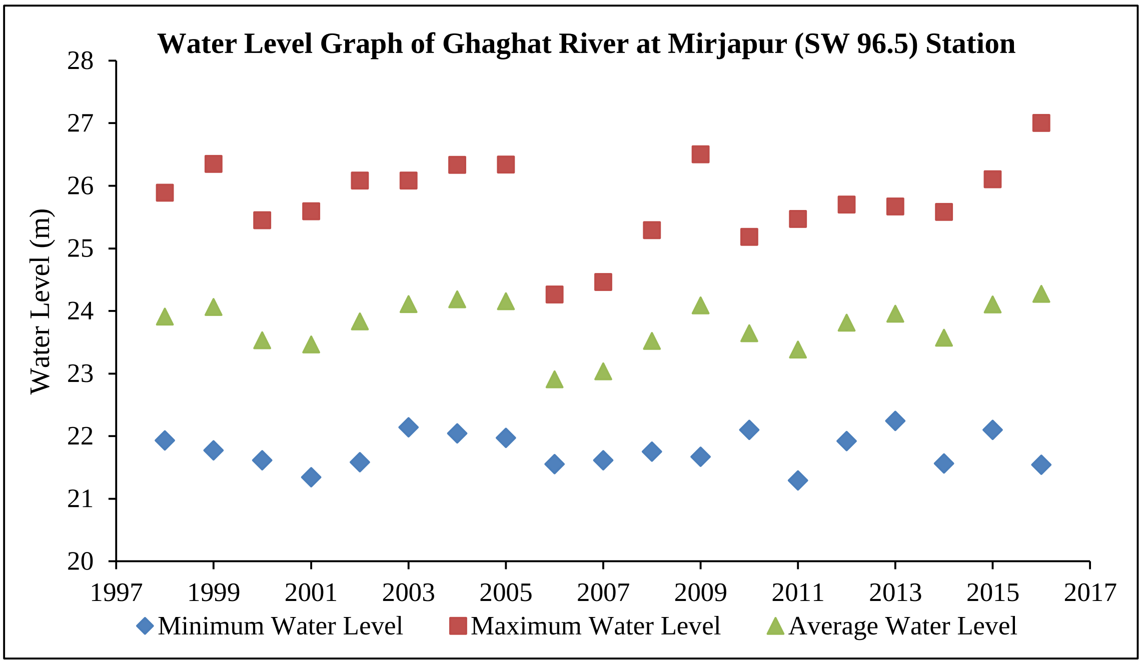

Figure 5.4: Water Level of Ghaghat River at Mirjapur (SW 96.5) Station

At Gaibandha water level is in slight increasing trend as well with maximum in 2004 and minimum in 2016. It is obviously clear that water level has decreased with slope towards downstream as a result water level at Islampur is lower than the water levels at Jafarganj Road crossing. Similar pattern has been found in case of water level at Mirjapur.

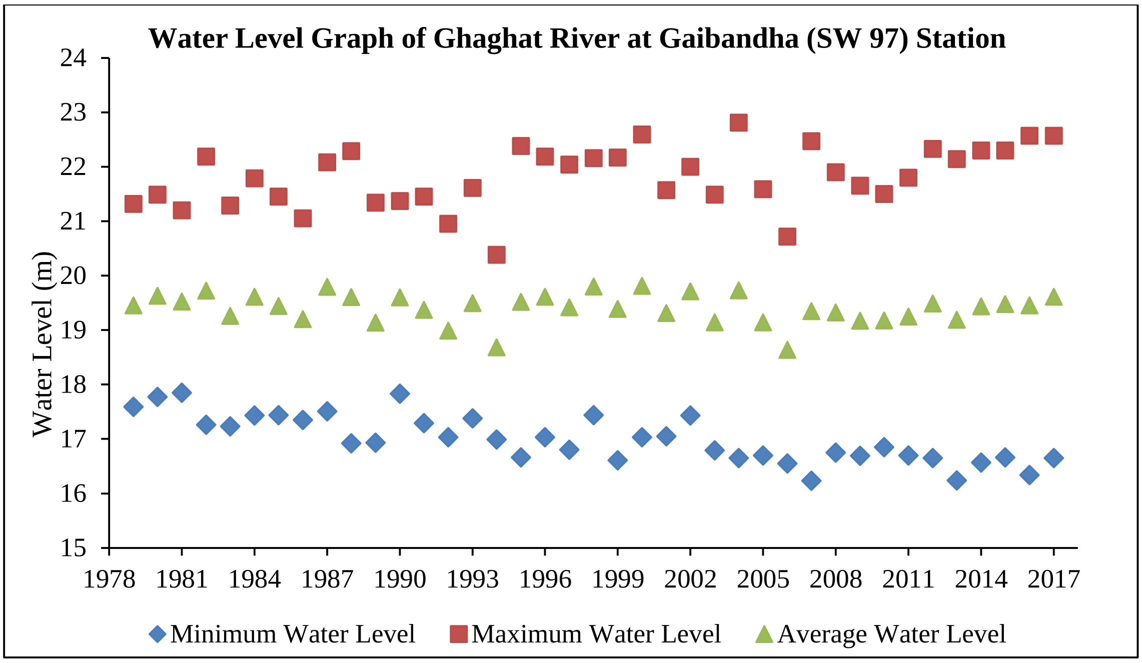

Figure 5.5: Water Level of Ghaghat River at Gaibandha (SW 97) Station

5.3 Model Setup

5.3.1 HEC-RAS 1D Model Set Up

The modeler develops the geometric data by either first drawing in the river system schematic on the Geometric Data window (figure 5.6) or by developing a schematic in HEC-RAS Mapper. First step of model development has to be drawn the reach of Ghaghat River in HECRAS interference with incorporation of RAS Mapper. The river system is drawn on a reach-by-reach basis, by pressing the River Reach button and then drawing in a reach from upstream to downstream (in the positive flow direction). Each reach is identified with name of Ghaghat River and a name of Ghaghat Reach.

The centerline, bank line, and river edge line of river shown in figure 5.7 have been automatically constructed in RAS Mapper after the river has been drawn in the geometry editor.

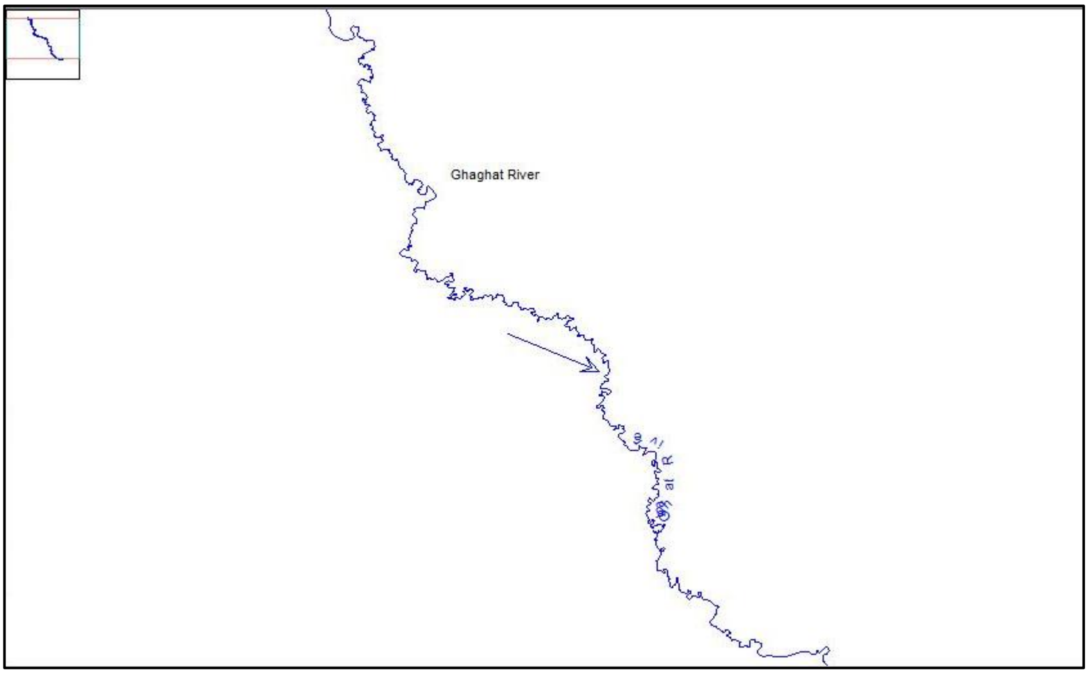

Figure 5.6: Ghaghat River reach on HEC-RAS

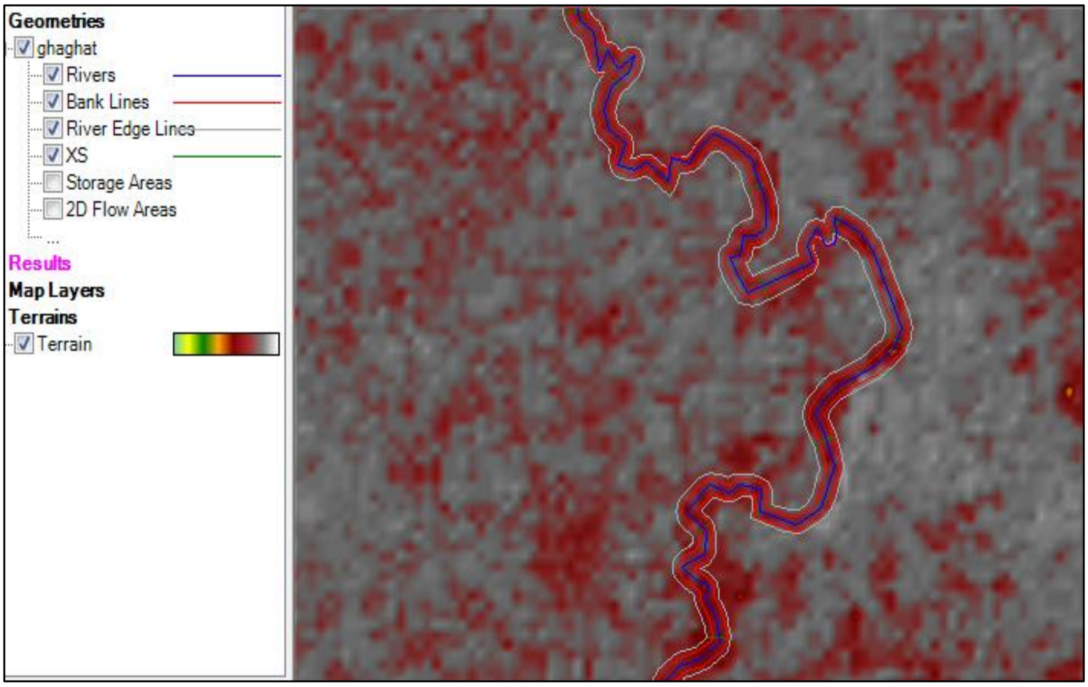

Figure 5.7: River Centerline, Bank line, and River edge line of Ghaghat River shown in RAS Mapper

5.3.2 Boundary Condition for 1D Model

The boundary condition is the conditions or phenomenon occurring at the boundaries of the model. There are several different types of boundary conditions available in HEC-RAS. They are Flow hydrograph, Stage hydrograph, Stage and flow hydrograph, Rating curve, Normal depth, Lateral inflow hydrograph, Groundwater inflow, Internal boundary stage and/or flow, etc.

The location of upstream discharge boundaries of Jafarganj Road Crossing (SW96A) and downstream water level boundary of Gaibandha (SW97) are shown in figure 5.8.

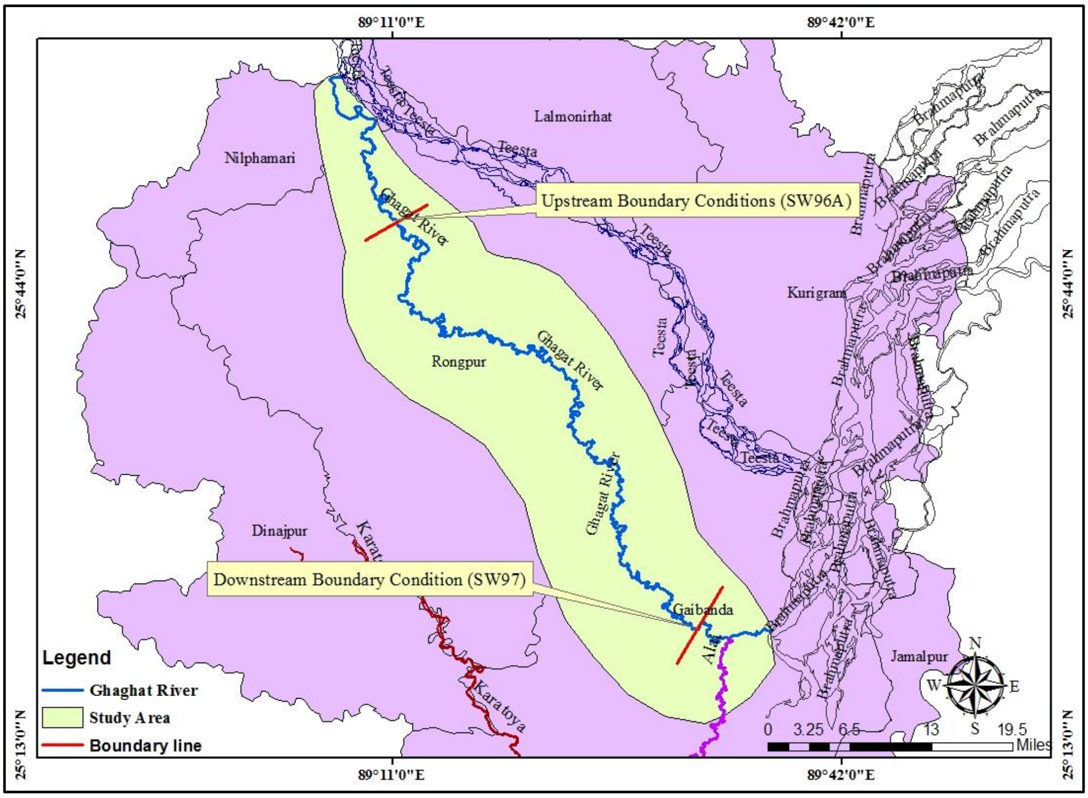

Figure 5.8: Locations of boundary condition

For the 1D hydrodynamic model of Ghaghat River, stage hydrograph data at Gaibandha (SW97) and discharge hydrographs data at Jafarganj Road Crossing (SW96A) for calibration and validation has been shown in figure 5.9, 5.10, 5.11 and 5.12 respectively.

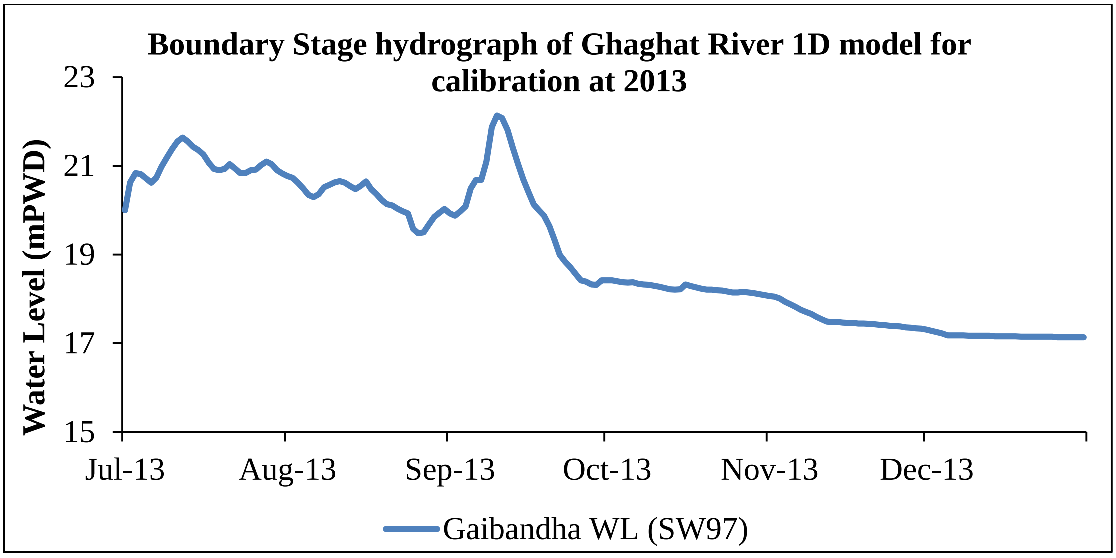

Figure 5.9: Boundary stage hydrograph for Ghaghat River for calibration 2013

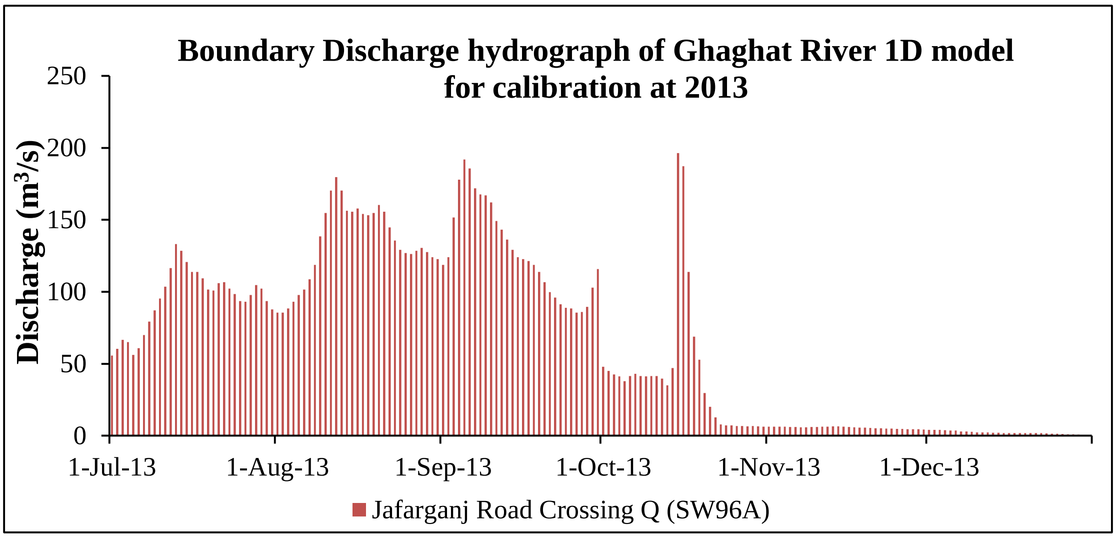

Figure 5.10: Boundary discharge hydrograph for Ghaghat River for calibration 2013

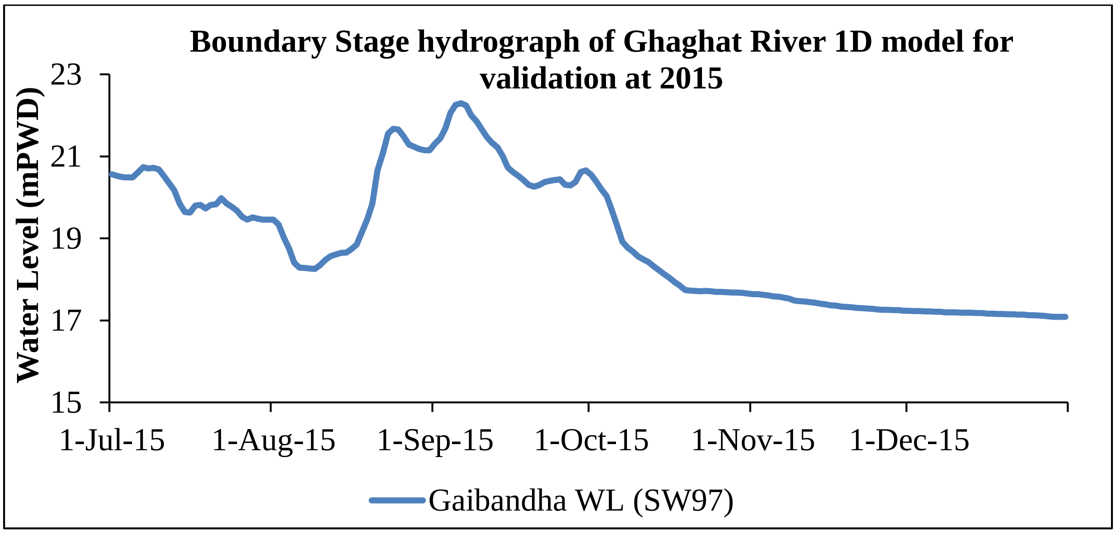

Figure 5.11: Boundary stage hydrograph for Ghaghat River for validation 2015

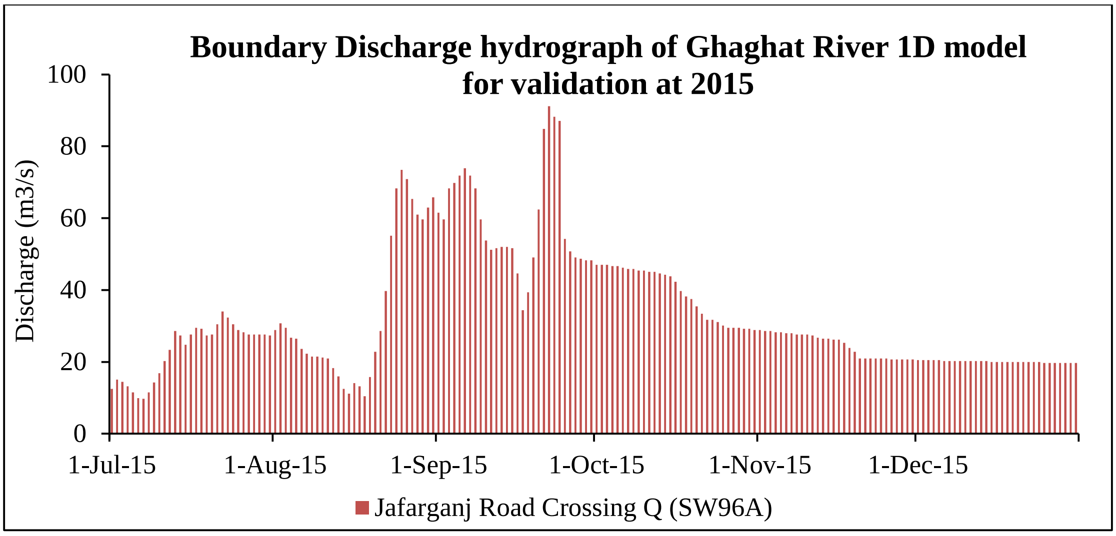

Figure 5.12: Boundary discharge hydrograph for Ghaghat River for validation 2015

5.3.3 HEC-RAS 1D-2D Coupled Model Set up

The Digital Elevation Model (DEM) of Bangladesh (in geographical coordinate system (GCS_WGS_1984)) has collected from the FTP server of the Shuttle Radar Topographic Mission (SRTM) of National Aeronautics and Space Administration (NASA). All the data in the DEM have been projected on to the Bangladesh Transverse Mercator (BTM). The data comprises of a resolution of 30m x 30m. The elevation of the DEM has been measured with respect to the mean sea level. In this study all the elevations including topography of river cross-sections, water surface elevation has been considered are 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 has been done.

DEM of Study Area

The DEM of three districts has been clipped from the modified digital elevation model using the Clipping Tool in Arc Toolbox. And after that, study area has been clipped from the DEM Nilphamari, Rangpur and Gaibandha district using the shape file of study area shown in figure 5.13.

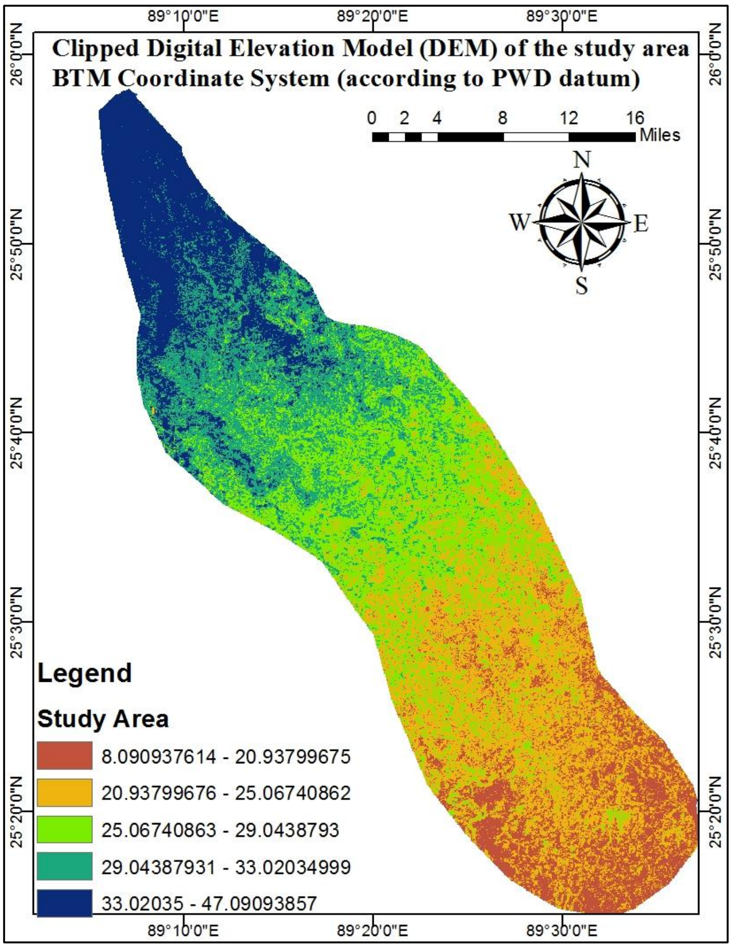

Figure 5.13: Clipping (DEM) of study area from modified digital elevation model

5.3.4 Processing on HEC-RAS

1D Hydrodynamic Model

Ghaghat River bathymetry has been incorporated in the Geometry Data window of HEC-RAS. The general approach to laying out cross sections is to ensure that the cross sections are perpendicular to the flow lines. Cross sections are located at intervals along a stream to characterize the flow carrying capability of the stream and its adjacent floodplain. The unit system is selected as SI units. The model comprises 36 number of cross-sections of the Ghaghat River named RMGHT1 to RMGHT36 which were imported for the development of the 1D hydrodynamic model. Later, 36 cross-sections have been placed through the length of the river. The bathymetry data of 2013 collected from BWDB and IWM has been incorporated in the cross-section data. The cross-sections of the Ghaghat River are shown in figure 5.14.

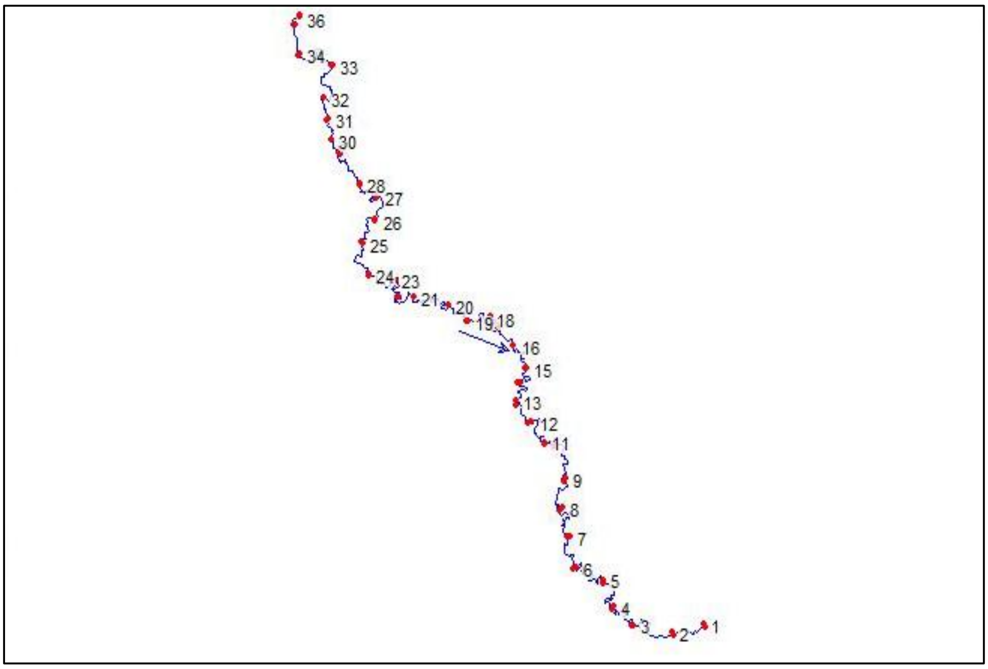

Figure 5.14: Cross-section of Ghaghat River in HEC-RAS

Then, the roughness of the river is incorporated manually, and the river is interpolated with a distance of 500 m between the cross sections as shown in figure 5.15.

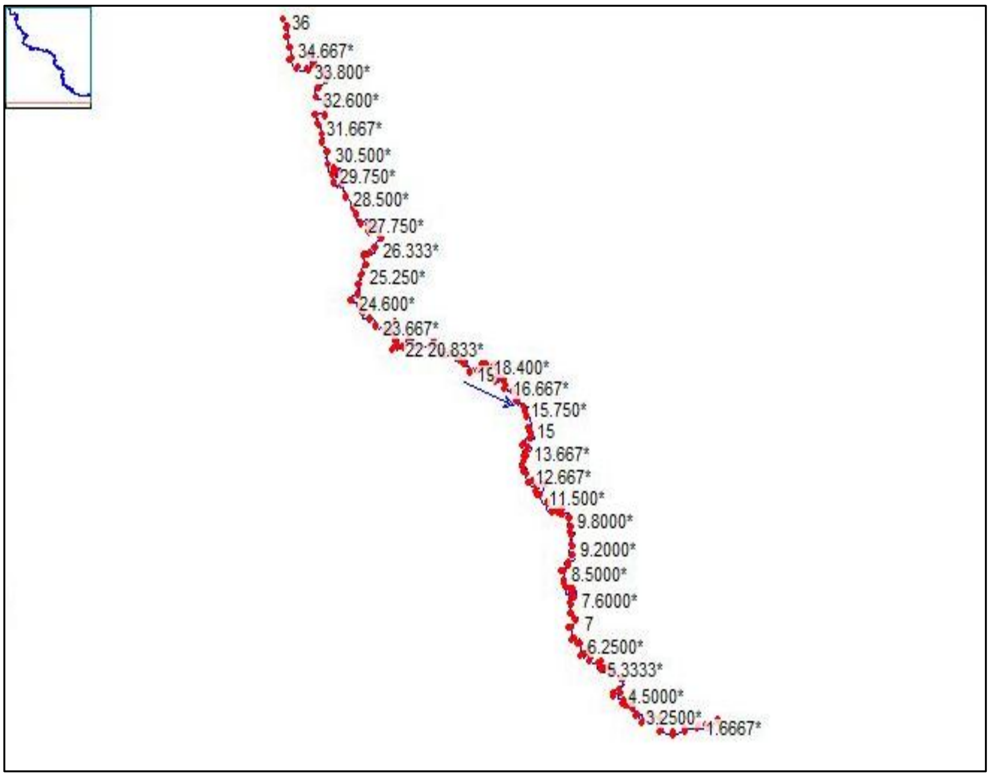

Figure 5.15: Interpolated Cross-sections of Ghaghat River

Developing a Terrain Model

A terrain layer is of primary importance for computing hydraulic properties (elevation, volume, elevation-wetted perimeter, elevation profiles etc.), inundation depths and floodplain boundaries. HEC-RAS supports the terrain model in Geo Tiff format. So, after preparing the 1D river bathymetry, the raster file of the study area is added using the new terrain layer tool of RAS-Mapper as shown in figure 5.16.

RAS Mapper converts this raster file into the Geo TIFF (*.tif) file format. Later, this terrain is used for pre-processing geometric data for 2D flow areas, computing flood depths and inundation boundaries from simulation results. However, prior to creating a terrain layer, the projection has been specified by selecting Bangladesh Transverse Mercator as an ESRI projection file (*.prj).

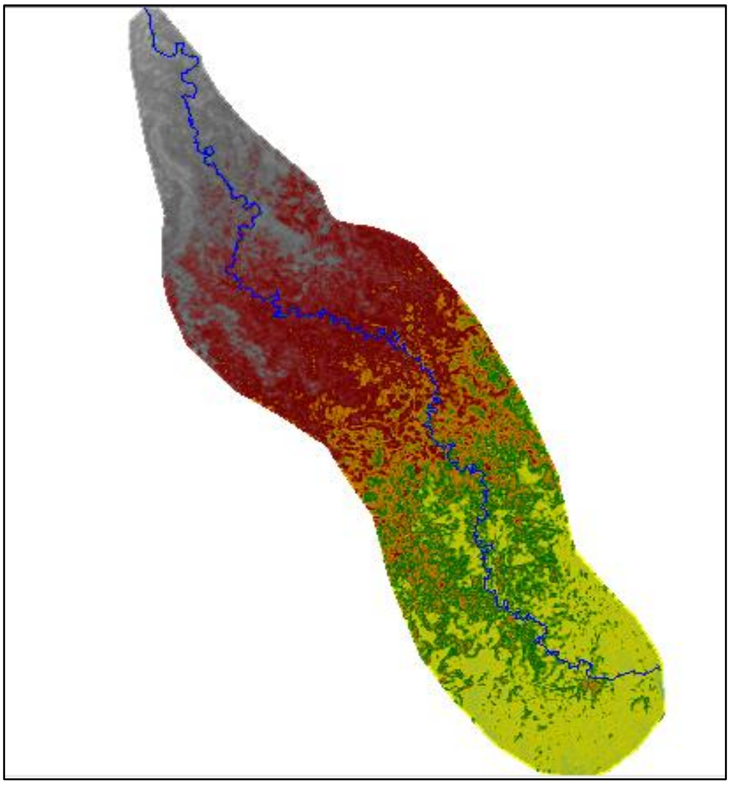

Figure 5.16: Incorporation of the Terrain of the study area in RAS-Mapper

Once a projection has been included, all the data has to be projected into the selected coordinate system. Then, this terrain file is opened in Geometry Editor window of HEC-RAS for generating 2D flow area.

2D Flow Area Computational Mesh

2D flow area is a region of a model in which the flow through that region is generated with the HEC-RAS 2D flow computational algorithm. 2D Flow area has been drawn by laying out a polygon that represents the outer boundary of the 2D flow area. RAS Mapper converts this raster file into the Geo TIFF (*.tif) file format. Later, this terrain is used for pre-processing geometric data for 2D flow areas, computing flood depths and inundation boundaries from simulation results. However, prior to creating a terrain layer, the projection has been specified by selecting Bangladesh Transverse Mercator as an ESRI projection file (*.prj). Once a projection has been included, all the data are to be projected into the selected coordinate system. Then, this terrain file is opened in Geometry Editor window of HEC-RAS for generating 2D flow area shown in figure 5.17.

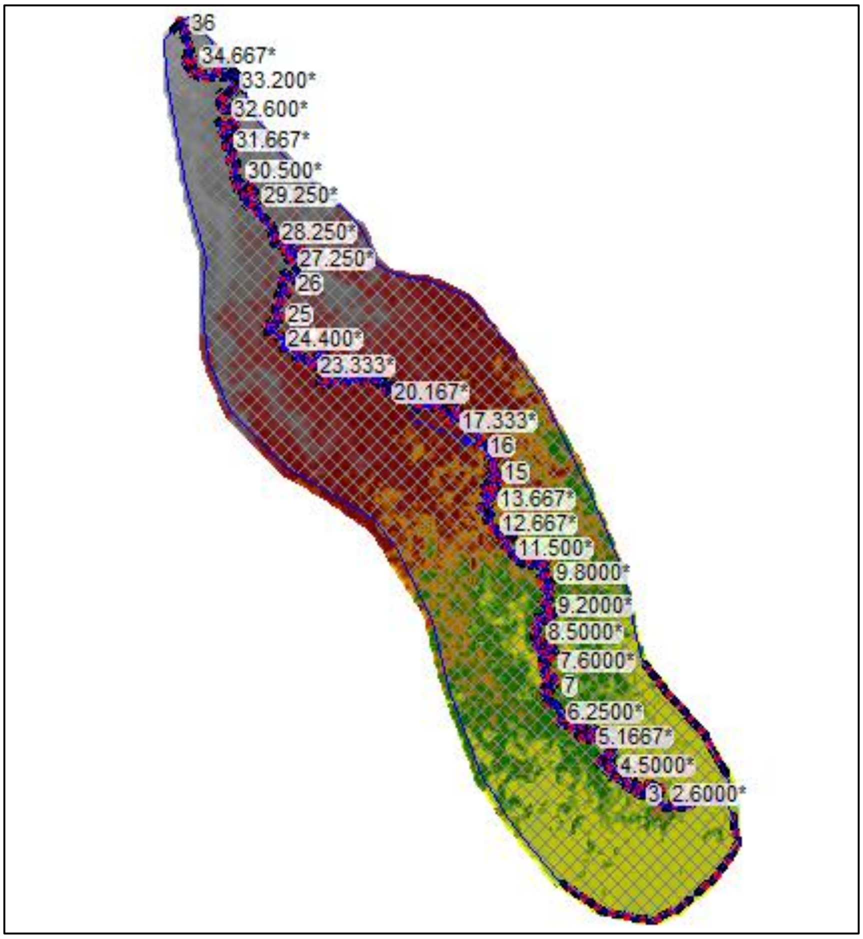

Figure 5.17: 2D flow area computational Mesh

1D-2D Coupling through Lateral Structure

A lateral structure can be connected to a 1D river reach or 2D flow area or 2D storage area. Here, the lateral structure is used to create a connection between the 1D river and 2D flow area, which has generated a movement of water between the 1D river and the 2D flow area. A series of twelve (six on each of the banks) lateral structures have been created in figure 5.18 from the upstream to downstream of the river as shown in figure 5.19. Red line of the figure represents where HEC-RAS has a link with the lateral structure to the 2D flow area. Figure 5.20 shows a vertical cross-section of one of the twelve lateral structures. The elevation of the connected lateral structure needs to be above the TW (Tail Water) cell min elevation.

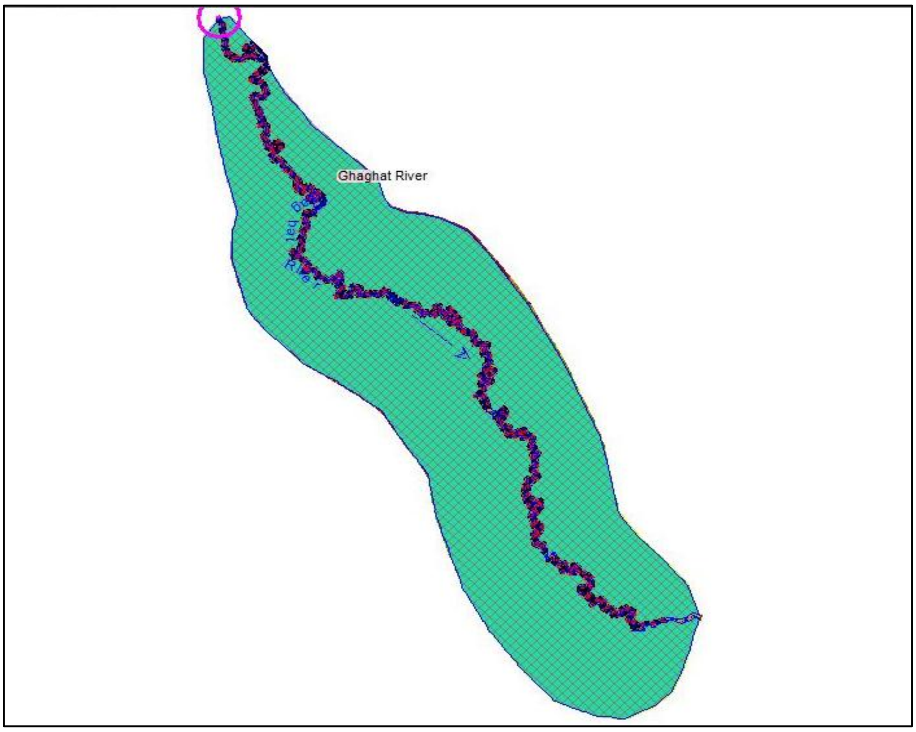

Figure 5.18: Incorporation of Lateral Structures

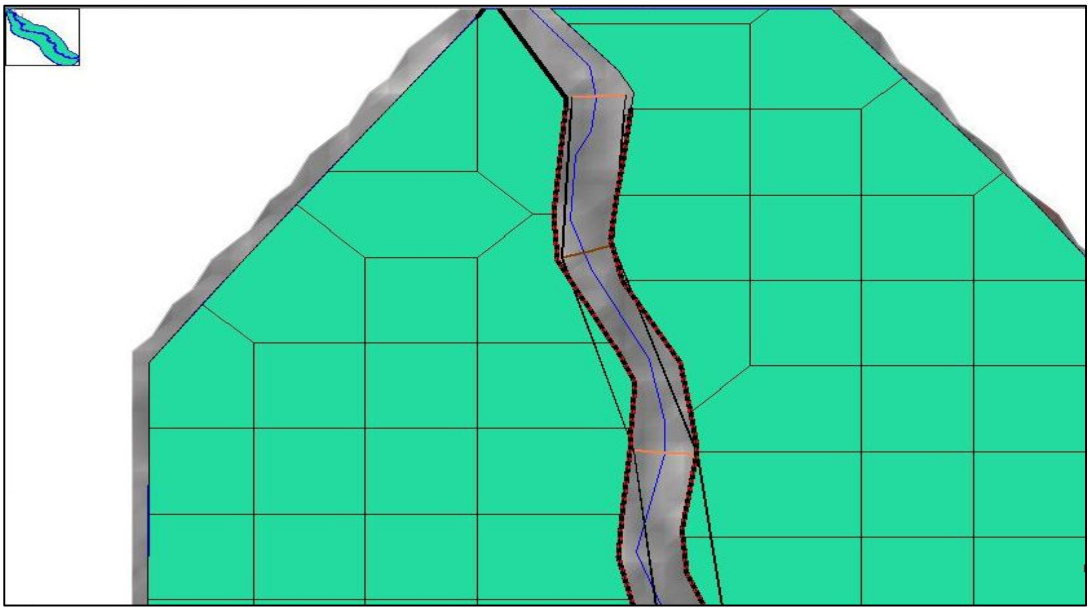

Figure 5.19: Lateral Structures provided both side of the River at upstream

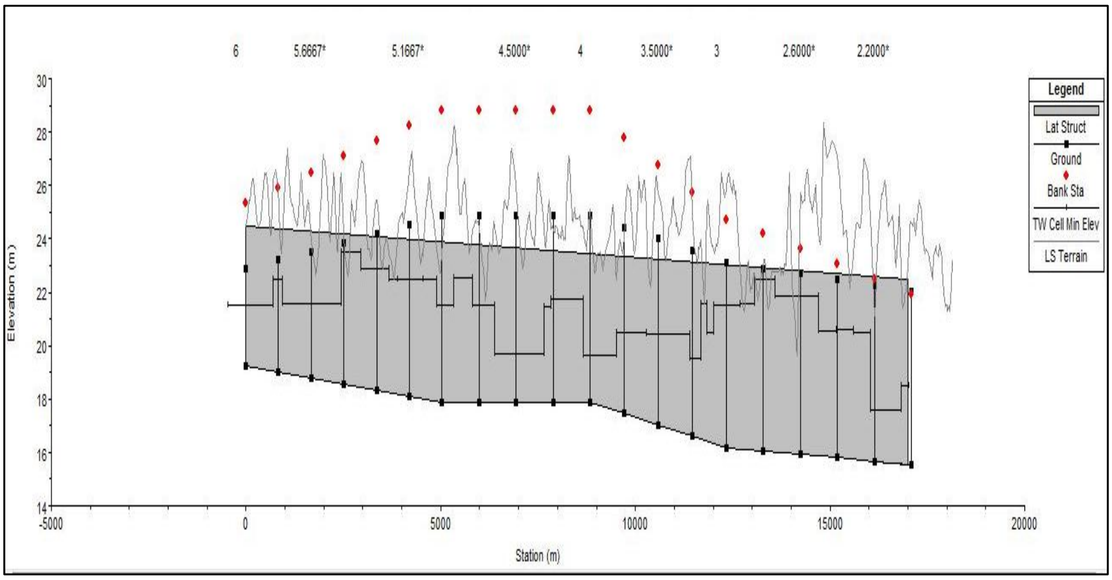

Figure 5.20: Elevation of 1 of the 12 Lateral Structures

Boundary Conditions

In this study, the one-dimensional hydrodynamic model has one upstream boundary and one downstream boundary. Here, the discharge hydrograph of Jafarganj Road Crossing (SW96A) and water level hydrograph of Gaibandha (SW97) is used as upstream and downstream boundary respectively. The upstream discharge boundary and downstream water level boundary condition for calibration and validation are shown in figure 5.21 and figure 5.22 respectively.

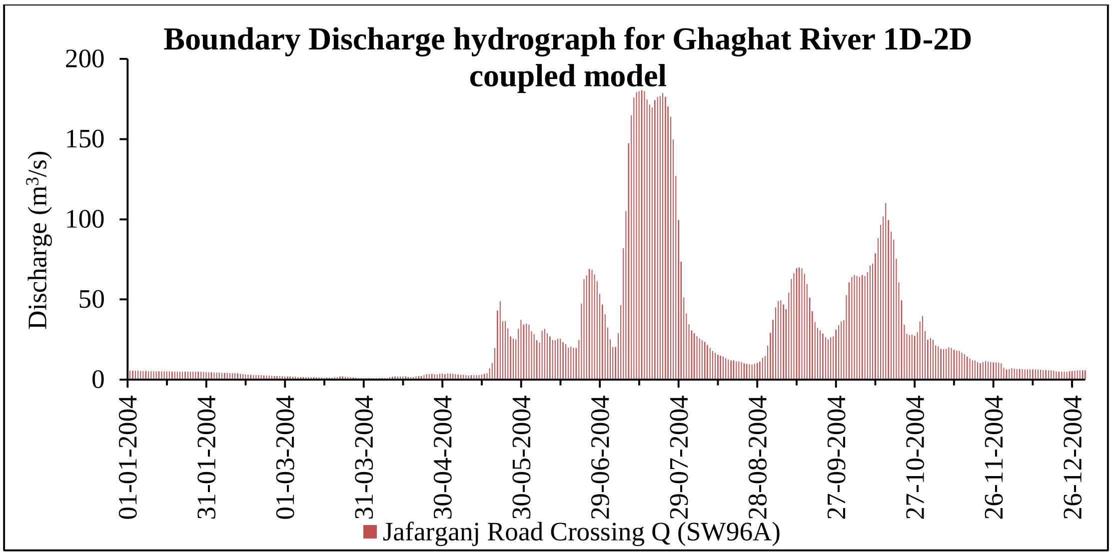

Figure 5.21: Boundary discharge hydrograph of Ghaghat River for 1D-2D coupled model for 2004

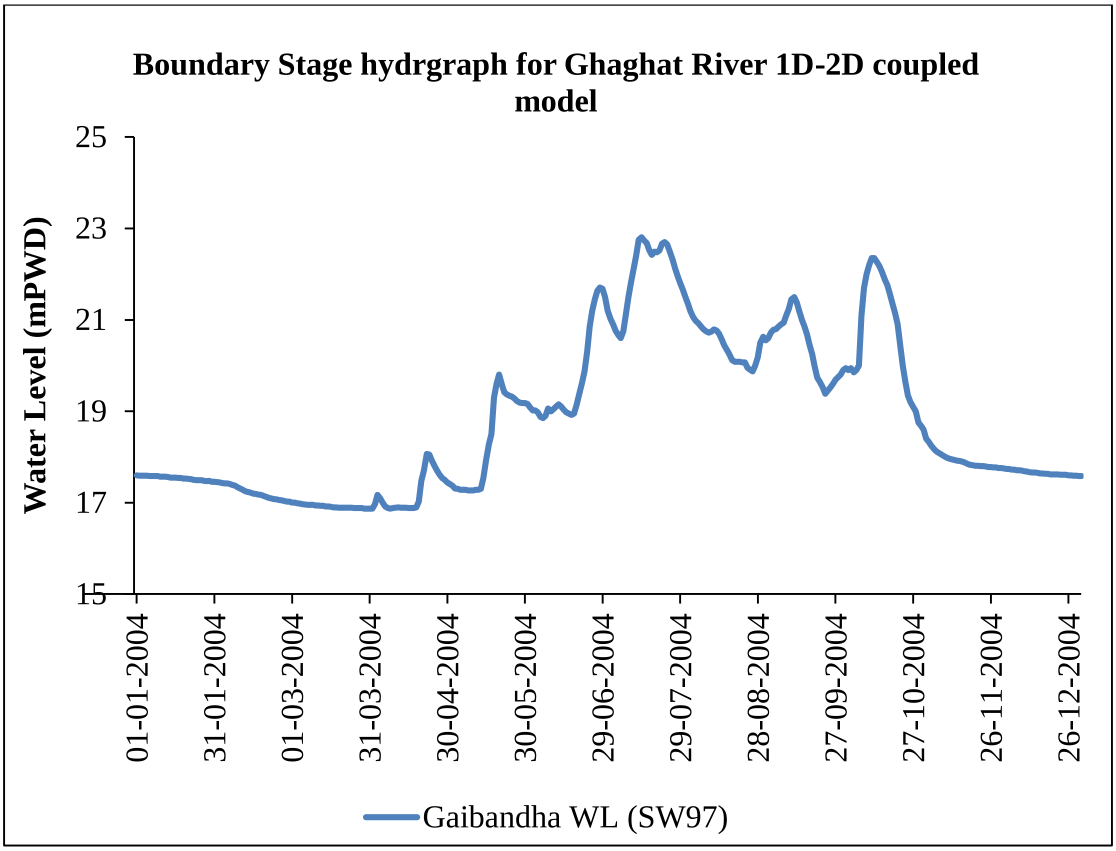

Figure 5.22: Boundary stage hydrograph of Ghaghat River for 1D-2D coupled model for 2004

Later, boundary conditions have been applied to the 2D flow area too. There are four peripheral boundaries incorporated in the model of the study area out of which two are inflow boundaries, and the other two are outflow boundaries as shown in figure 5.23.

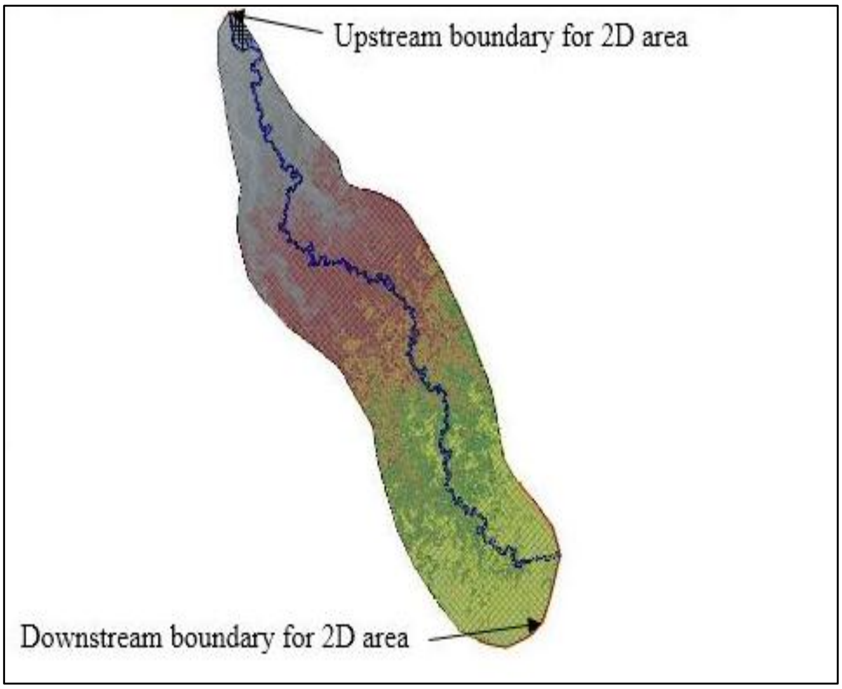

Figure 5.23: Incorporation of upper and lower boundary condition for 2D Flow Area

Two inflow boundaries are used on the upper periphery to taking the inflow into 2D flow area. Another two boundaries are used in the lower periphery for the purpose of passing out the water from the floodplain. In these boundaries, normal depth condition has been used.

5.4 Calibration and Validation of Ghaghat River 1D-2D coupled Model

5.4.1 Calibration & Validation of the 1D Model

In this study, the one-dimensional model of Ghaghat River system has been calibrated and validated for the year of 2013 and 2015 respectively. Flow hydrograph and stage hydrograph are used as the upstream and downstream boundary condition respectively. Then, the mean daily discharge data at the observed station is compared with the model simulated daily discharge. Generally, the water level time series is compared instead of the flow series. The model is calibrated and validated at Mirjapur (SW 96.5) station of Ghaghat River. This station is selected for calibration and validation because it is the intermediate station between the upstream and downstream station of Ghaghat River. Then, the mean daily water level data at the observed station is compared with the model simulated daily water level.

5.4.2 Calibration

In this study, simulation is done for the one-dimensional model of the Ghaghat River using the daily hydrograph for five months from July to November. Manning's n is the main calibration parameter of the HEC-RAS model. The result shows that the upstream water surface elevation is increased by increasing Manning's roughness coefficient value. These are consistent with the law of water flowing.

Various sets of Manning's roughness coefficients, n = 0.014 – 0.024, 0.024 -0.027 are adopted for various simulations. All simulations are run in unsteady state condition. The result shows that the upstream water surface elevation is increased by increasing Manning's roughness coefficient value. These are consistent with the law of water flowing. Finally, the roughness of n = 0.020 from downstream to cross-section station 18 and n = 0.021 for rest of the rivers of the system. The comparison of observed and simulated flow hydrograph at Mirjapur (SW 95.6) station has been shown in figure 5.24.

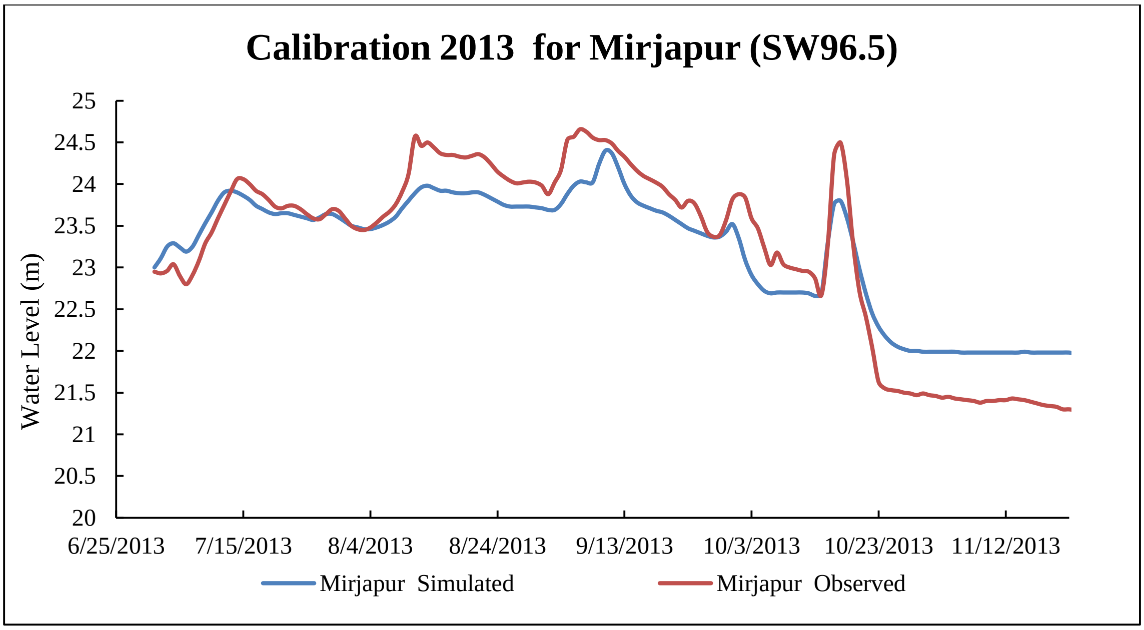

Figure 5.24: Calibration of Ghaghat River 1D model

Figure 5.24 shows that the trend and shape of the observed and hydrograph are almost similar pattern. The simulated water level and observed water level almost matches in the monsoon period from June to November. There are little differences after October to November.

5.4.3 Validation

Using the calibrated Manning's roughness coefficient (n) value, validation has been performed for the year 2015. The validation has also shown a satisfactory result. The comparison of observed and simulated discharge hydrograph at Mirjapur (SW 95.6) has been shown in figure 5.25. Figure 5.25 shows the simulated stage hydrograph is in close agreement with observed hydrograph.

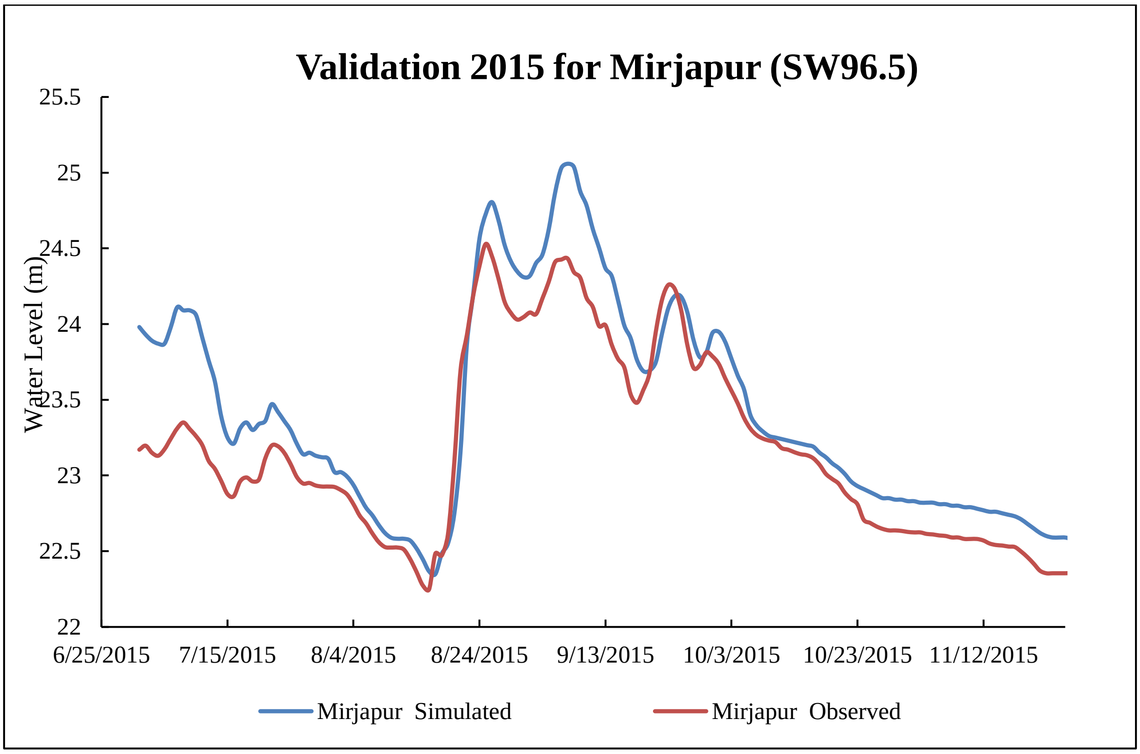

Figure 5.25: Validation of Ghaghat River 1D model

5.5 Model Performance Evaluation

Apart from the visual comparison, the model has been assessed statistically as well using two widely used statistical indicators- Coefficient of Determination (R^2) and Nash Sutcliffe Efficiency (NSE). In the case of calibration shown in figure 5.26, the coefficient of determination of R^2 and NSE have been found 0.9596 and 0.956 respectively which indicate that the simulated value is very close to the observed value and also within the satisfactory range.

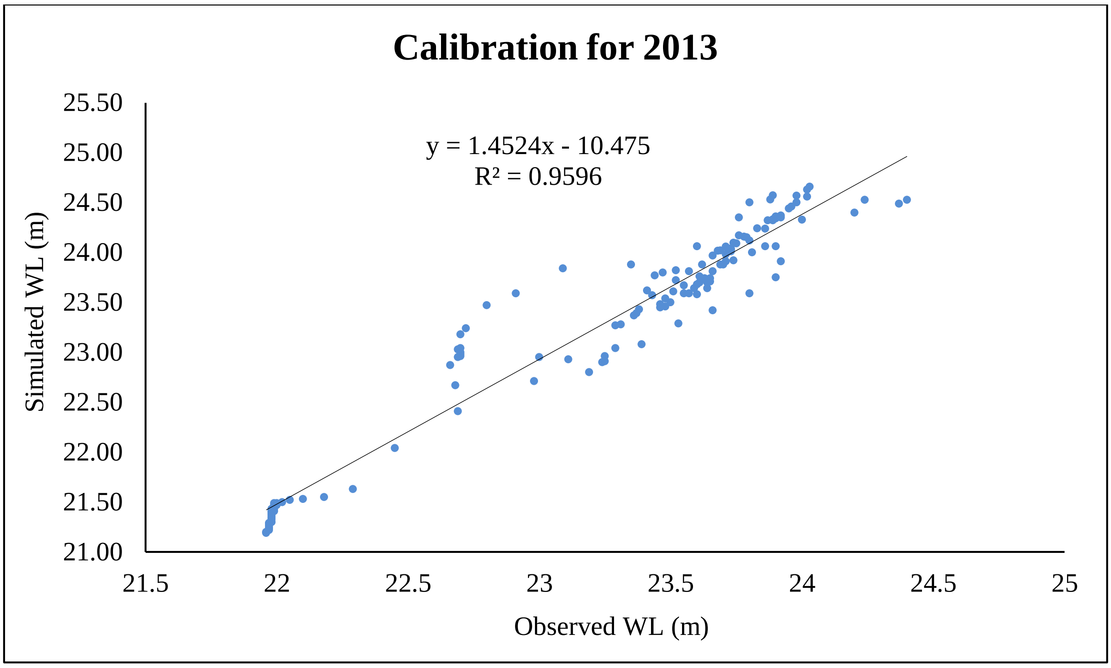

Figure 5.26: Scatter plot of observed vs simulated water level at Mirjapur (SW96.5) Station for calibration year 2013

In the case of validation shown in figure 5.27, the coefficient of determination R^2 and Nash and Sutcliffe Efficiency (NSE) have been found 0.9027 and 0.730 respectively which indicate a good correlation between the observed and simulated data and indicates the model's accuracy for further analysis.

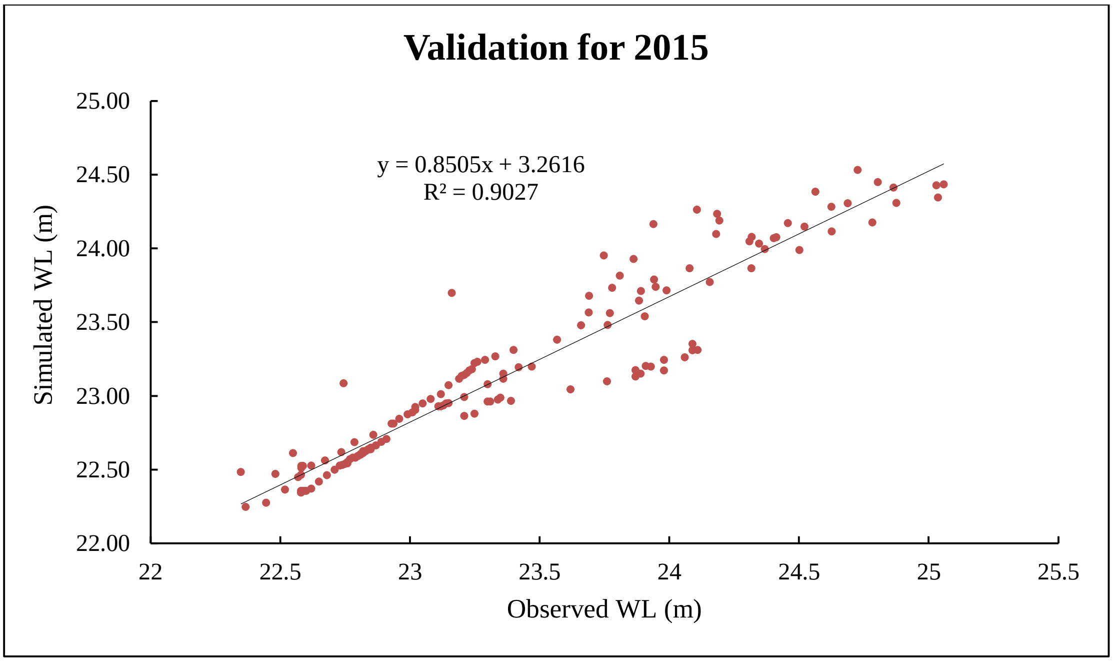

Figure 5.27: Scatter plot of observed vs simulated water level at Mirjapur (SW96.5) Station for validation year 2015

5.6 Qualitative Comparison Between Model Simulated and Observed Flood Map (Satellite Image)

After calibration and validation of the 1D model, a 1D-2D coupled model has set up to simulate the flood inundation in the floodplain. However, it is necessary to validate the simulated 2D flood inundation as well. The 2D flood inundation is usually validated comparing with the observed FFWC produced flood map (Tazin, 2018; Nishat, 2017).

In this section, the qualitative comparison is done among FFWC observed map, satellite image and simulated model. The Qualitative comparison has done for flooding situations. Figure 5.28 shows the comparison among FFWC produced flood inundation map and model generated flood inundation map for flood conditions. From figure 5.28 it has observed that the inundation among FFWC observed map, satellite image and simulated model are adequately alike on 23rd August, 2004.

From figure 5.29 it has also observed that the inundation among FFWC observed map, satellite image and simulated model from HEC-RAS 1D-2D coupled model are adequately alike on 5th August, 2007.

Common places of the inundated area between observed flood map and simulated flood map have been marked by different color circles and ellipse for easy visualization. Comparison among FFWC observed map, satellite image and simulated result has found satisfactory.

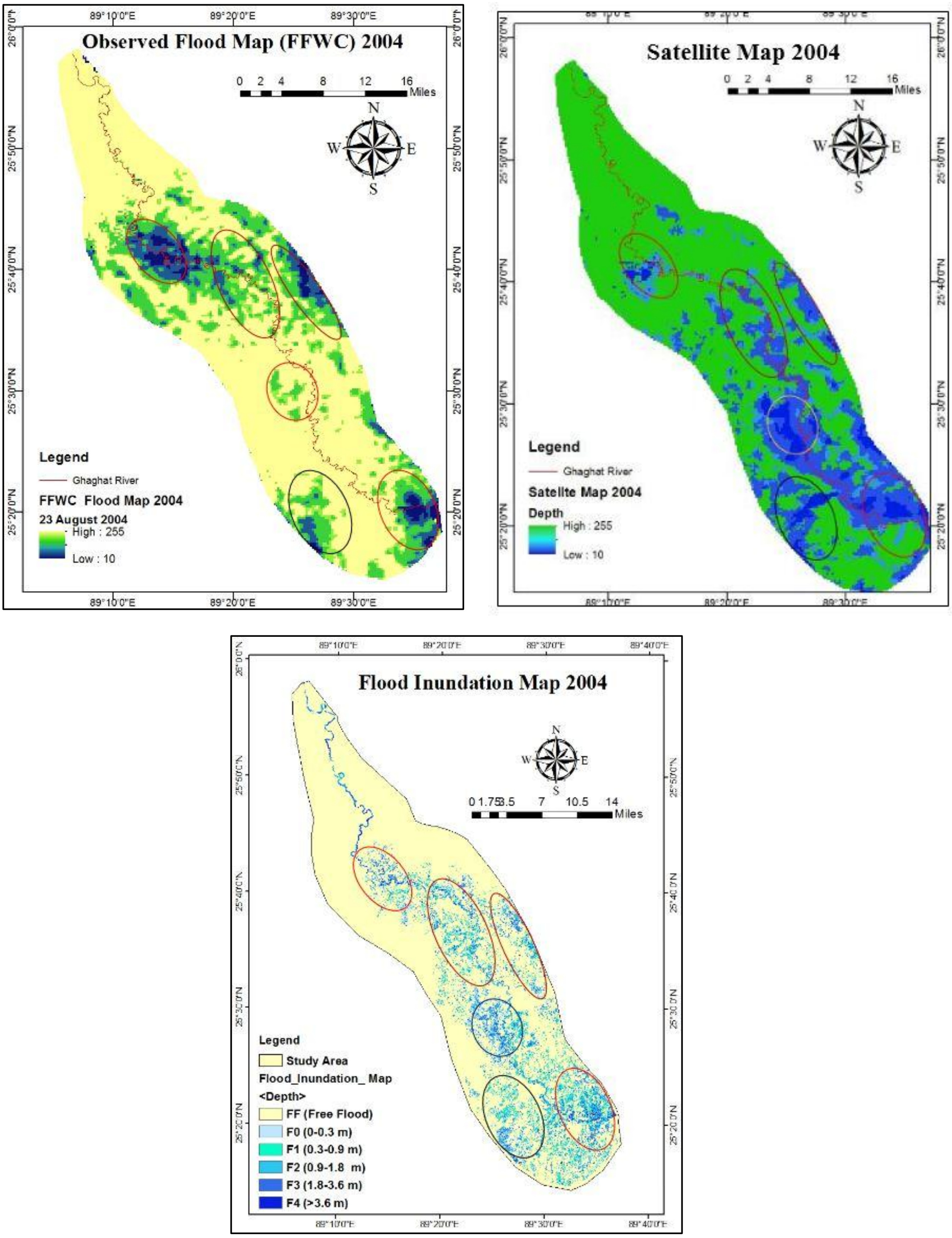

Figure 5.28: Qualitative comparison between the flood maps for 23rd August, 2004 (a) observed FFWC produced map (b) satellite image (c) simulated flood map from HEC-RAS 1D-2D coupled model

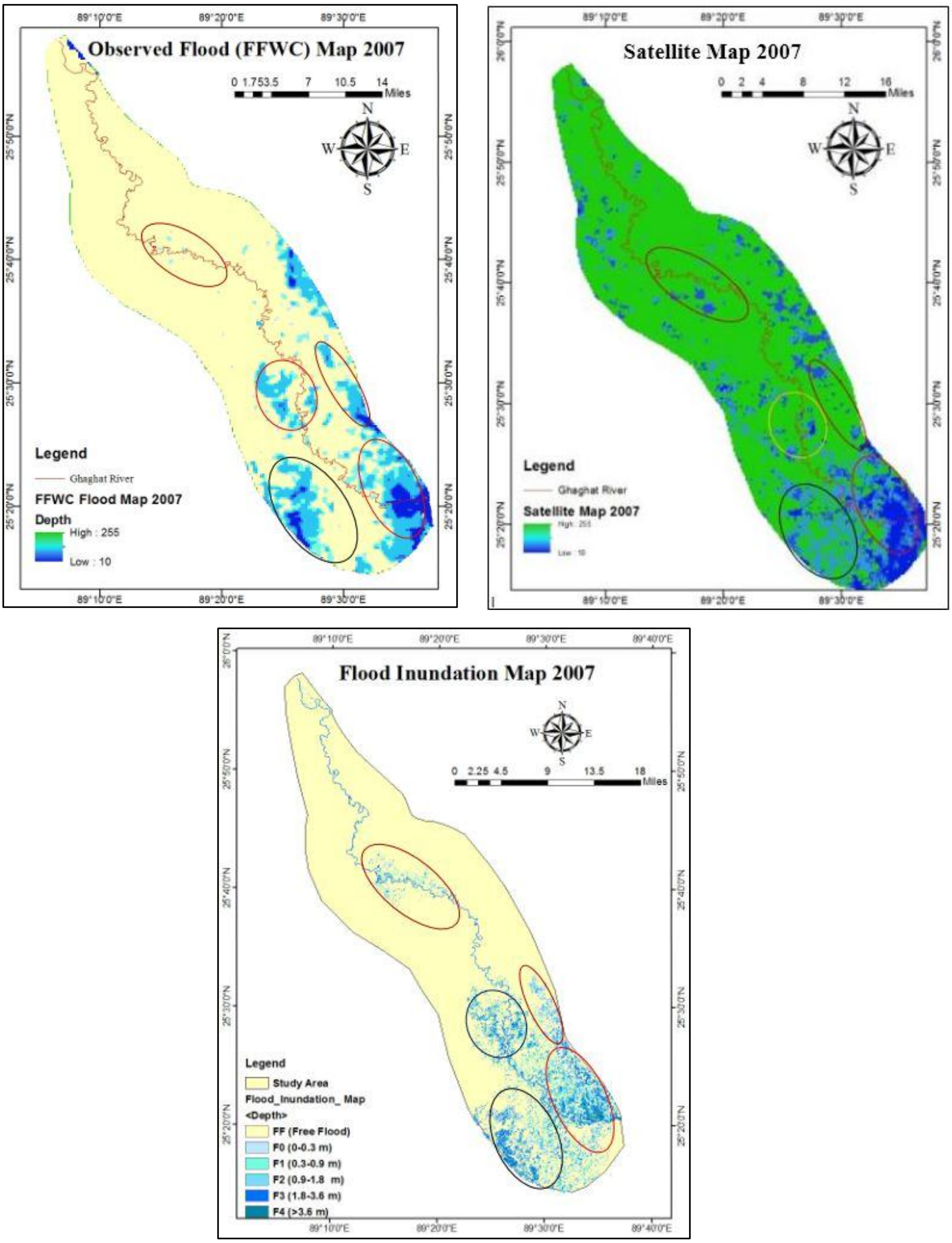

Figure 5.29: Qualitative comparison between the flood maps for 5th August, 2007 (a) observed FFWC produced map (b) satellite image (c) simulated flood map from HEC-RAS 1D-2D coupled model

CHAPTER 6
RESULTS AND DISCUSSIONS

6.1 General

In this chapter an analysis of the output and discusses the performance of the HEC-RAS model. Visual observation and statistical measures were used to evaluate the performance of the model. In this study, NSE values were calculated and reported to provide an indication of model performance relative to other studies.

As described earlier, the effects of variations in flood inundation map due to 1D/2D couple model in historical events has analyzed.

After creating flood inundation map three scenarios have been selected for flood mitigation of Ghaghat River. These three scenarios have then been analyzed to represent the flood inundation map and to identify the reduction of flood inundation area with respect to previously model generated map.

6.2 Flood Inundation Map and Depth Analysis

Floodplain delineation is done by HEC RAS 5.0.1 software itself and shown in RAS Mapper. No GIS help is needed here. Shape file of different flood extend can be produced for different time. Then the shape file has been exported into ARC-GIS and calculated the area of inundation including the main channel.

6.3 Analysis of Historical Flood Events of Ghaghat River

6.3.1 Flood Inundation Maps of Historical Flood Events

After calibration and validation of the 1D-2D coupled model, it has been simulated for the historical flood events of 2004, 2007, 2011, 2012 and 2017. Later, these have used for prepare historical flood inundation maps.

The flood inundation maps of the study area consist of three districts named Nilphamari, Rangpur and Gaibandha. This study area covers total 1532 km^2 where Gaibandha, Nilphamari, Rangpur districts cover 566.42 km^2, 13.81 km^2 and 951.75 km^2 respectively.

The simulated flood inundation maps of 2004, 2007, 2011, 2012 and 2017 are shown in figure 6.1, 6.2, 6.3, 6.4 and 6.5 respectively.

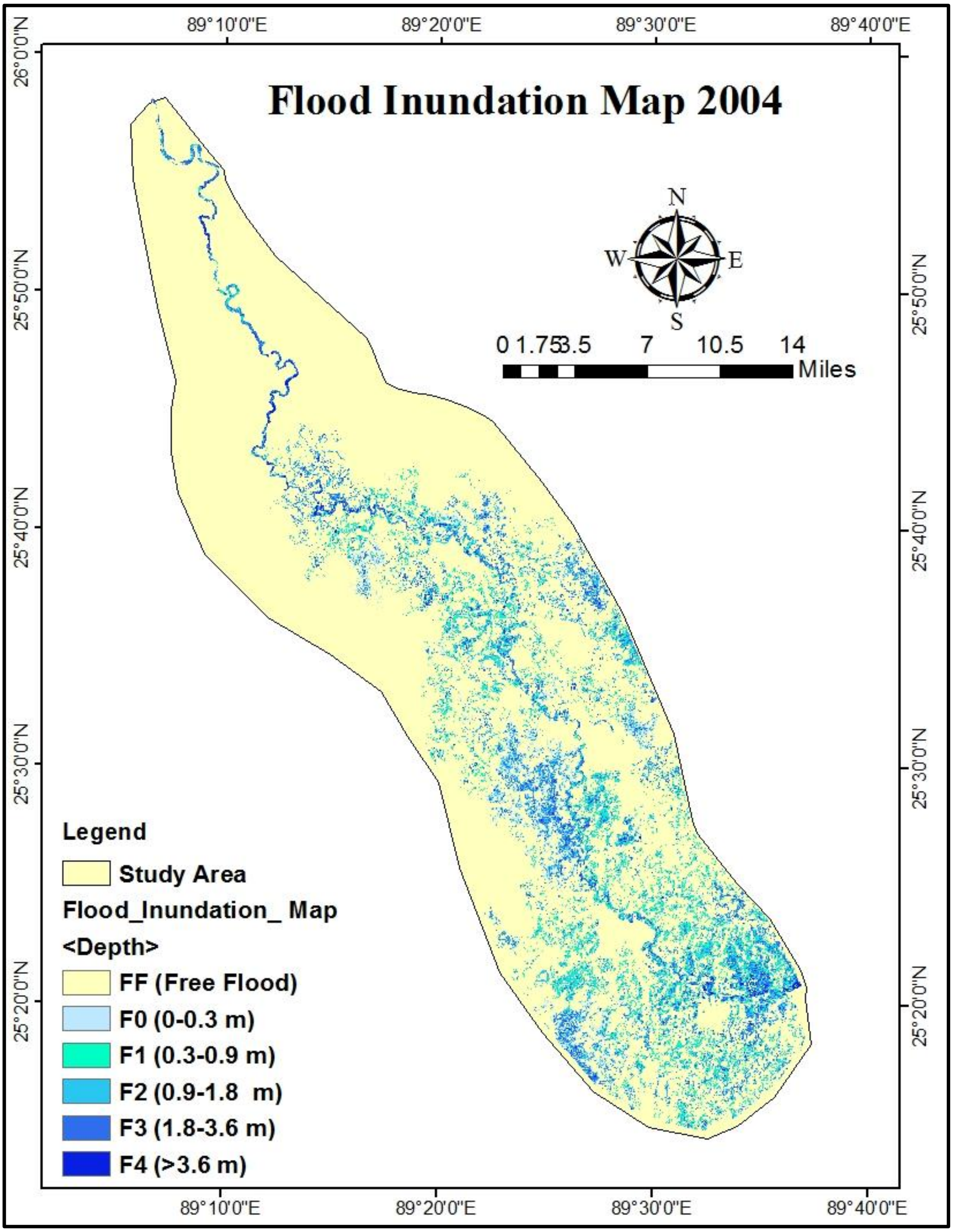

Figure 6.1: Flood inundation map of 2004 based on maximum flood depth

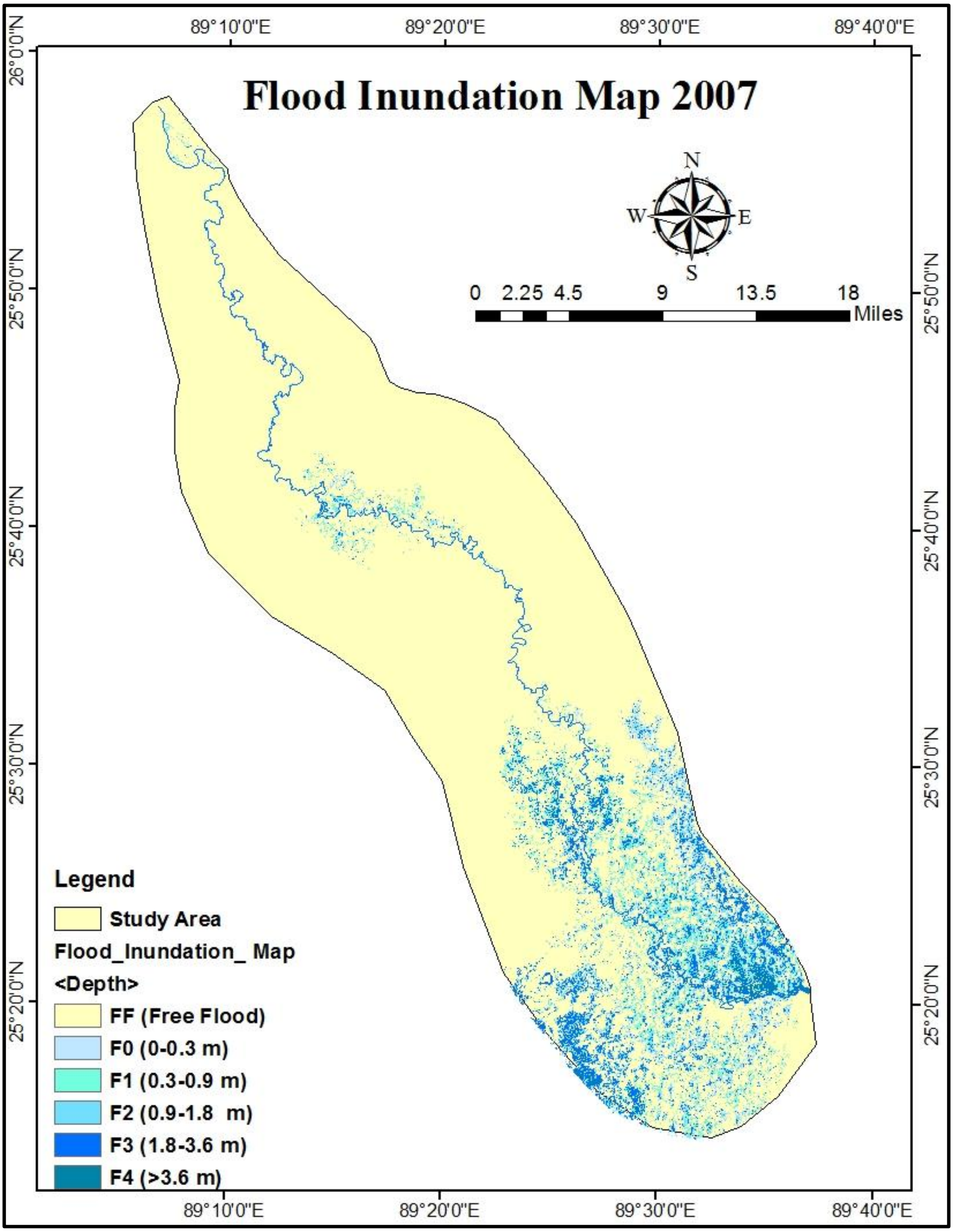

Figure 6.2: Flood inundation map of 2007 based on maximum flood depth

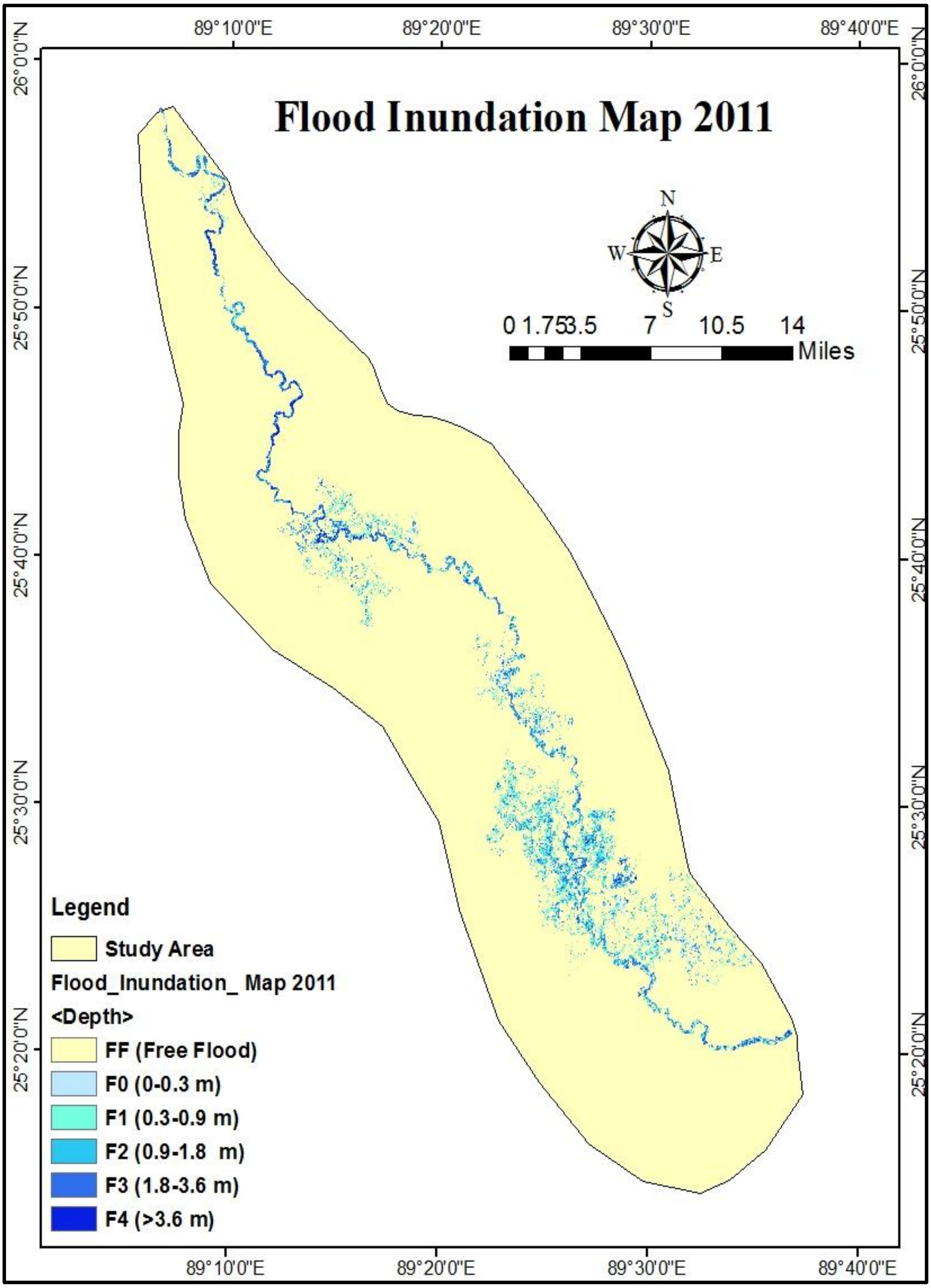

Figure 6.3: Flood inundation map of 2011 based on maximum flood depth

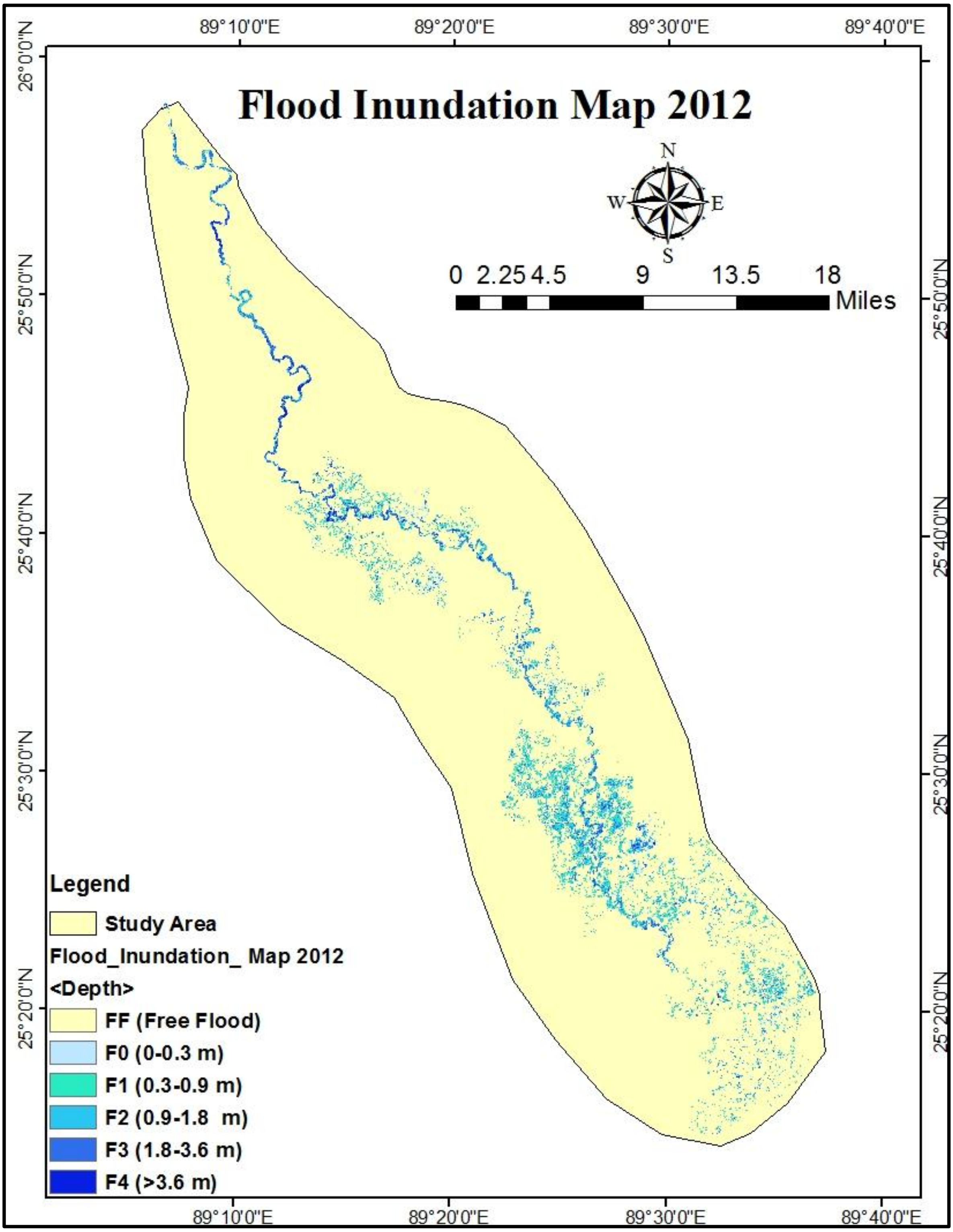

Figure 6.4: Flood inundation map of 2012 based on maximum flood depth

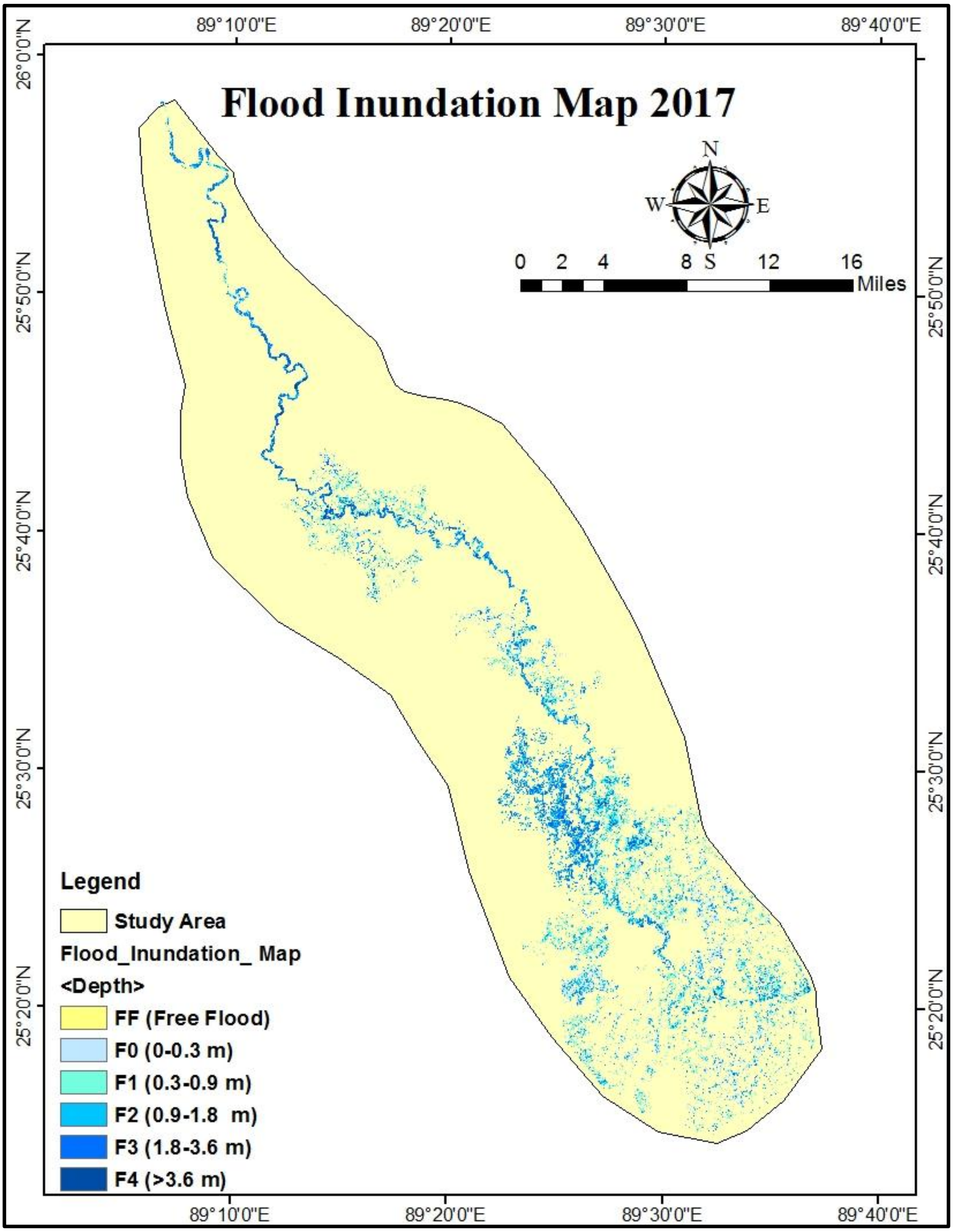

Figure 6.5: Flood inundation map of 2017 based on maximum flood depth

Table 6.1 shows that the flood affected area is the highest for the flood of 2004. The flood inundation area is found nearly 295.34 km^2 which is about 19.27% of the study area. This result coincides with the real flood statistics of Bangladesh. In flood event of 2007, 2011, 2012 and 2017 inundated area were 25.90 km^2, 89.17 km^2, 107.70 km^2 and 136.64 km^2 respectively.

Table 6.1: Flood Affected Areas on the flood of period (2004-2017)

Year	Flood affected area (sq. km)	Flood inundated (%)
2004	295.34	19.28
2007	157.79	10.3
2011	89.17	5.82
2012	107.70	7.03
2017	136.64	8.92

The summary of the District-wise inundated area for historical flood years 2004, 2007, 2011, 2012 and 2017 have been summarized in table 6.2.

Table 6.2: District-wise inundated area for historical Flood period (2004-2017)

Districts	Gaibandha (sq. km)	Inundated (%) of Gaibandha	Rangpur (sq. km)	Inundated (%) of Rangpur
2004	207.43	36.62	87.91	9.24
2007	100.54	17.75	43.29	4.55
2011	58.21	10.28	30.96	3.25
2012	70.47	12.44	37.23	3.91
2017	94.98	16.77	41.66	4.38

The flood affected areas under Nilphamari covers 13.37 km^2 of the study area which is not inundated. Rangpur and Gaibandha covers 207.43 km^2 and 87.91 km^2 respectively for 2004 which is maximum among all the flood year. The percentage of inundation area under Gaibandha and Rangpur are 36.62% and 9.24% respectively for 2004. Among all the districts Gaibandha is the most affected area. From rest of them Rangpur also affected by flood. However, the scenarios increased in magnitude and extent with time.

6.3.2 Flood Inundation Depth of Historical Flood Events

Depth map have been created in RAS Mapper for the particular dates and then those raster file has been exported into GIS. In the study, inundated areas are defined into five qualitative inundation depth classes like inundation depth from 0 to 0.3 is classified as Class 1 (F0), 0.3 to 0.9 m has been classified as class 2 (F1), 0.9 m to 1.8 m inundation depth has been classified as class 3 (F2), inundation depth from 1.8 m to 3.6 m has been classified as class 4 (F3) and inundation depth more than 3.6 m has been classified as class 5 (F4). This inundation classification has developed by the National Water Management Plan (NWMP).

Table 6.3, 6.4 represents the comparison on variation of inundation extent area in different year (2004-2017) according to flood depth.

Table 6.3: Comparison of Inundated area in different year (2004-2017) according to Flood depth

Inundated Area (sq. Km) in particular year (2004-2017)					
Classification of flood	**2004**	**2007**	**2011**	**2012**	**2017**
F0 (0-0.3 m)	29.1	15.0	9.2	14.1	17.3
F1 (0.3-0.9 m)	47.5	12.3	12.4	17.8	23.9
F2 (0.9-1.8 m)	136.3	32.5	21.4	24.7	30.3
F3 (1.8-3.6 m)	50.2	68.9	33.7	38.1	49.6
F4 (>3.6 m)	32.2	29.1	12.4	13.0	15.5
Total	295.4	157.8	89.2	107.7	136.7

Table 6.3 shows that, most of the area experienced maximum flooding in the year 2004 and minimum flooding in the year 2011 among the years considered. Gaibandha and Rangpur districts experienced greater flood depth in most of the years within the study area. The maximum mean flood depth experienced by in 2004 which covers 295.34 km^2 and the minimum mean flood depth occurred in 2011 which covers 89.17 km^2 areas. For the flood year 2004, mean flood depth of the study area lied with the range of 0.9m to 1.8m with maximum area covering 136.3 km^2 and with the range of 0m to 0.3m minimum area covering 29.1 km^2. For the flood year 2007, mean flood depth of the study area lied with the range of 1.8m to 3.6m with maximum area covering 68.9 km^2 and with the range of 0.3m to 0.9m minimum area covering 12.3 km^2. For the flood year 2011, mean flood depth of the study area lied with the range of 1.8m to 3.6m with maximum area covering 33.7 km^2 and with the range of 0m to 0.3m minimum area covering 9.2 km^2. For the flood year 2012, mean flood depth of the study area lied with the range of 1.8m to 3.6m with maximum area covering 38.1 km^2 and with the range of greater than 3.6m minimum area covering 13.0 km^2. For the flood year 2017, mean flood depth of the study area lied with the range of 1.8m to 3.6m with maximum area covering 49.6 km^2 and with a range greater than 3.6m minimum area covering 15.5 km^2.

Table 6.4: Comparison of percentage of flood inundation area in different year (2004-2017) according to flood depth

Comparison of percentage (%) of flood inundated Area (sq. Km) in particular year (2004-2017)					
Classification of flood	**2004**	**2007**	**2011**	**2012**	**2017**
F0 (0-0.3 m)	1.9	0.98	0.6	0.92	1.13
F1 (0.3-0.9 m)	3.1	0.8	0.81	1.16	1.56
F2 (0.9-1.8 m)	8.9	2.12	1.4	1.61	1.98
F3 (1.8-3.6 m)	3.28	4.5	2.2	2.49	3.24
F4 (>3.6 m)	2.1	1.9	0.81	0.85	1.01
Total (%)	19.28	10.3	5.82	7.03	8.92

Table 6.4 represents the percentage of flood inundation area in different year (2004-2017) according to flood depth. The percentage of total inundated area with respect to classification of flood depth is found 2004. The percentage of maximum flood depth greater than 3.6m are found 2.1%, 1.9%, 1.01%, 0.85% and 0.81% for 2004, 2007, 2017, 2012 and 2011 respectively. The maximum percentage of flood depth from 1.8m to 3.6m are found 4.5%, 3.28%, 3.24%, 2.49% and 2.2% for 2007, 2004, 2017, 2012, and 2011 respectively. The maximum percentage of flood depth from 0.9m to 1.8m are found 8.9%, 2.12%, 1.98%, 1.61% and 1.4% for 2004, 2007, 2017, 2012 and 2011 respectively. The maximum percentage of flood depth from 0.3m to 0.9m are found 3.1%, 1.56%, 1.16%, 0.81% and 0.8% for 2004, 2017, 2012, 2011 and 2007 respectively. The summary of the flood inundation area according to classification of flood for 2004, 2007, 2011, 2012 and 2017 respectively have been represented in figure 6.6.

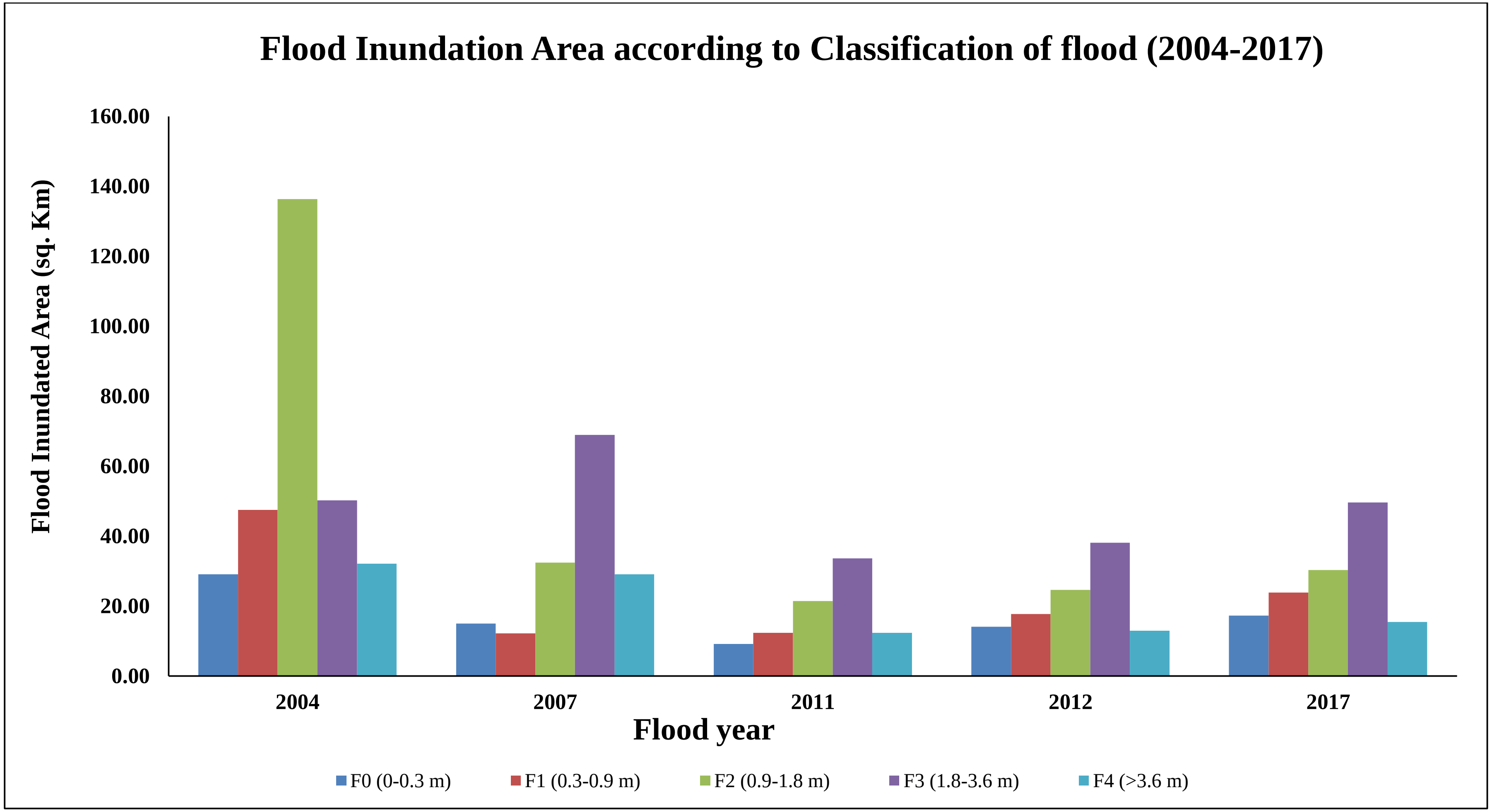

Figure 6.6: Flood Inundation Area according to Classification of flood (2004-2017)

6.4 Flood Mitigation Measures

There exist a number of structural and non-structural means for flood mitigation and management. Embankment, dams and flood control reservoirs, improvement of channel capacity, diversions and flood expansion areas to convey a flood wave belong to the category of structural flood mitigation measures. It has therefore clear that three planning solutions addressed in this study which include embankment systems, dredging of cross section or channel modification and combination of these two systems so long as they are able to reduce flood inundation area entirely. For flood mitigation, the following scenarios have been developed by HEC-RAS 1D/2D coupled model –

Table 6.5: Flood Mitigation Scenarios

Flood Mitigation Scenarios	
Scenario 1:	**Embankment**
Scenario 1.1	Raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank (figure 6.10)
Scenario 1.2	Raising the existing embankment height by 0.5 meter up to 41.5 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing left bank and right bank from 41.5 kilometers to 57 kilometers and 27.5 kilometers to 57 kilometers respectively (figure 6.12)
Scenario 1.3	Raising the existing embankment height by 1 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and 0.5m from 37 kilometers to 41.5 kilometers at left bank and construction of new embankment of 1m height from 27.5 kilometers to 37 kilometers at right bank and construction of new embankment of 0.5m height from existing left bank and right bank from 41.5 kilometers to 57 kilometers and 37 kilometers to 57 kilometers respectively (figure 6.14)

Scenario 1.4	Raising the existing embankment height by 1.25 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers from downstream at right bank and construction of new embankment of 1.25m height from 27.5 kilometers to 37 kilometers at right bank and construction of new embankment of 1m height from 37 kilometers to 57 kilometers at left and right bank and construction of new embankment of 0.5m height from 57 kilometers to 77 kilometers at left and right bank (figure 6.16)
Scenario 2:	**Dredging**
Scenario 2.1	Dredging 0.5 meter from the cross-sections 2 to 9 (2.8-31.6 kilometers) and cross-sections 15 to 22 (49.5-73 kilometers) (figure 6.21)
Scenario 2.2	Dredging 1.0 meter from cross-sections 2 to 9 (2.8-31.6 kilometers) and cross-sections 15 to 22 (49.5-73 kilometers) (figure 6.23)
Scenario 2.3	Dredging 1.5 meters from the cross-sections 2 to 9 (2.8-31.6 kilometers) and 1.0 meter from the cross-sections 15 to 22 (49.5-73 kilometers) (figure 6.25)
Scenario 3:	**Combination of embankment and dredging**
Scenario 3.1	Raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and Dredging 0.5 meter from cross-sections 15 to 22 (49.5-73 kilometers) (figure 6.28)
Scenario 3.2	Raising the existing embankment height by 1 meter up to 20 kilometers from downstream at left bank and right bank and raising the existing embankment height by 1.2 meter from 20 kilometers to 37 kilometers from downstream at left bank and from 20 kilometers to 27.5 kilometers at right bank and construction of new embankment of 1.2m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and Dredging 1.0 meter from cross-sections 15 to 22 (49.5-73 kilometers) (figure 6.30)

6.4.1 Embankment

Flood embankments like levees increase the channel depth of a river, raising its bankfull discharge and reducing the risk of flood. They increase the cross-sectional area of the river and therefore its hydraulic radius. To protect the floodplain from inundation, embankment can be provided one or both side of the river in different segments of river.

The Ghaghat left embankment has a height of 0.5m to 4.6m, a crest width of 1.0m to 5.0m, and side slope of 1:0.4 to 1:2.5 at the country side and 1:0.9 to 1:2.6 at the river side (North West Regional Study (FAP-2)). Ghaghat left embankment continued 41.5 km and right embankment 27.5 km through the left and right side of the river (BWDB). The proposed option for providing embankment through the left and right bank of Ghaghat River to mitigate flood inundation area are as follows:

Scenario 1.1 Raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing right bank up to next 9.5 kilometers at right bank

Scenario 1.2 Raising the existing embankment height by 0.5 meter up to 41.5 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing left bank and right bank from 41.5 kilometers to 57 kilometers and 27.5 kilometers to 57 kilometers respectively

Scenario 1.3 Raising the existing embankment height by 1 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and 0.5m from 37 kilometers to 41.5 kilometers at left bank and construction of new embankment of 1m height from 27.5 kilometers to 37 kilometers at right bank and construction of new embankment of 0.5m height from existing left bank and right bank from 41.5 kilometers to 57 kilometers and 37 kilometers to 57 kilometers respectively

Scenario 1.4 Raising the existing embankment height by 1.25 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers from downstream at right bank and construction of new embankment of 1.25m height from 27.5

kilometers to 37 kilometers at right bank and construction of new embankment of 1m height from 37 kilometers to 57 kilometers at left and right bank and construction of new embankment of 0.5m height from 57 kilometers to 77 kilometers at left and right bank

After selection of cross-section shown in figure 6.7 and 6.8, the embankment has been incorporated in HEC-RAS 1D/2D coupled model. It has been simulated for the historical flood events of 2004 as it is maximum.

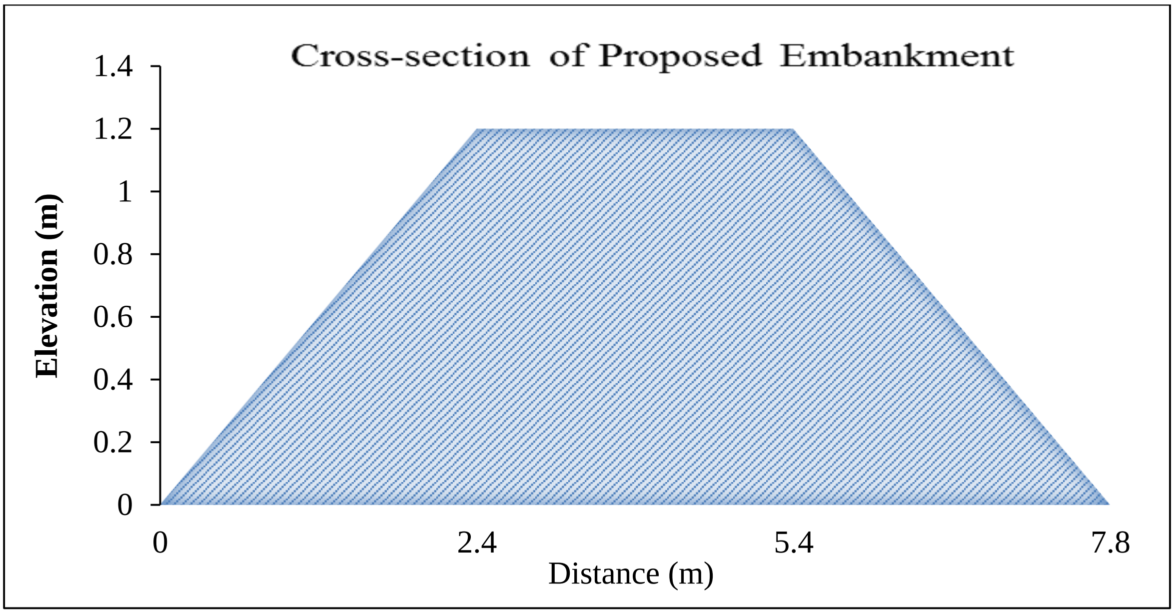

Figure 6.7: Cross-section of Proposed Embankment

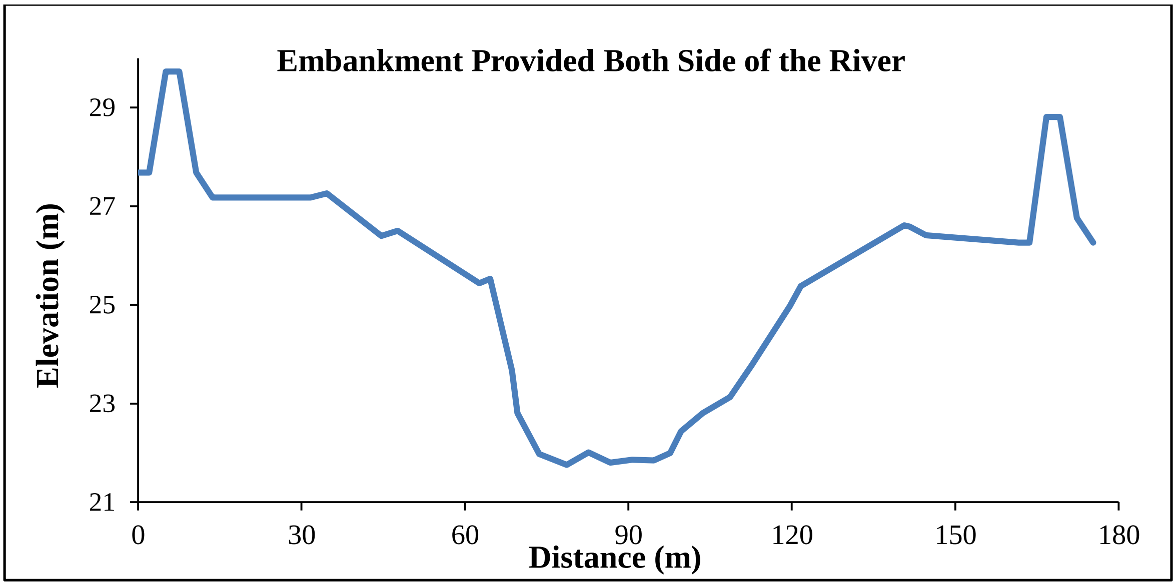

Figure 6.8: Cross-section of River with Ghaghat left and right Embankment

Later, they are used to prepare flood inundation maps due to raising height and extension of left and right bank embankment in which inundation area are to be checked. Same procedure has been followed for the others scenarios.

Scenario 1: Existing Embankment

Figure 6.9 showed that the existing embankment has placed on the downstream of the Ghaghat River. Even though the river has an embankment on its downstream side, there is a significant amount of flooding in the research area. A flood inundation map has been created for the year 2004 after creating a hydrodynamic model on HEC-RAS with an existing embankment. From the inundation map it has been found that 295.34 square km area has flooded. The area has about 19.27% of total area of the study area.

Scenario 1: **Base flood inundation map 2004**

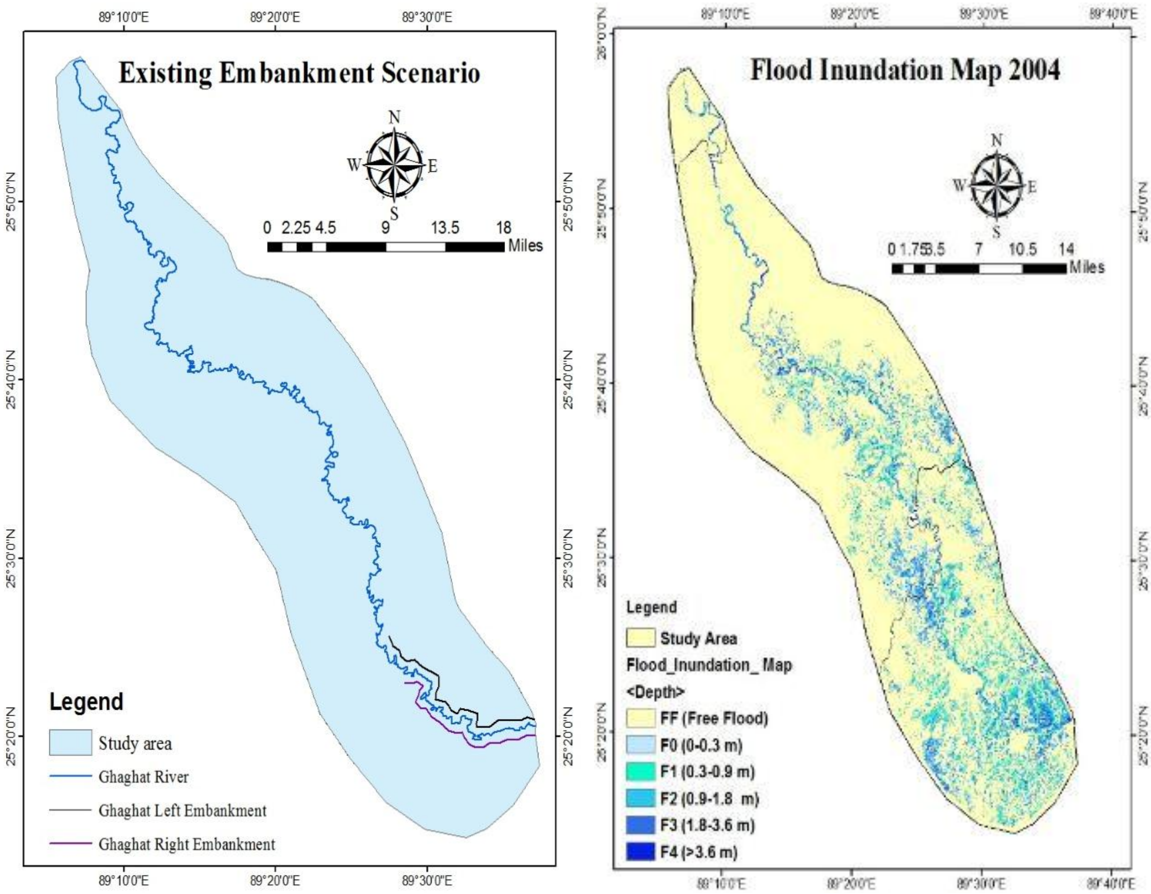

Figure 6.9: Flood Inundation map of 2004 based on Existing Scenario

For flood mitigation raising the embankment height or extension of existing embankment from downstream can be an option. That’s why here the embankment height has been increased by 0.5 meters from its varying existing height 22 to 22.5 meter at downstream in left and right side of the river in scenario 1.1. As Ghaghat left embankment continued 41.5 km and right embankment 27.5 km through the left and right side of the river so construction of new embankment of 9.5 km has been introduced at right side of Ghaghat River. Later this change incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.10.

Scenario 1.1: Raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing right bank up to 37 kilometers at right bank

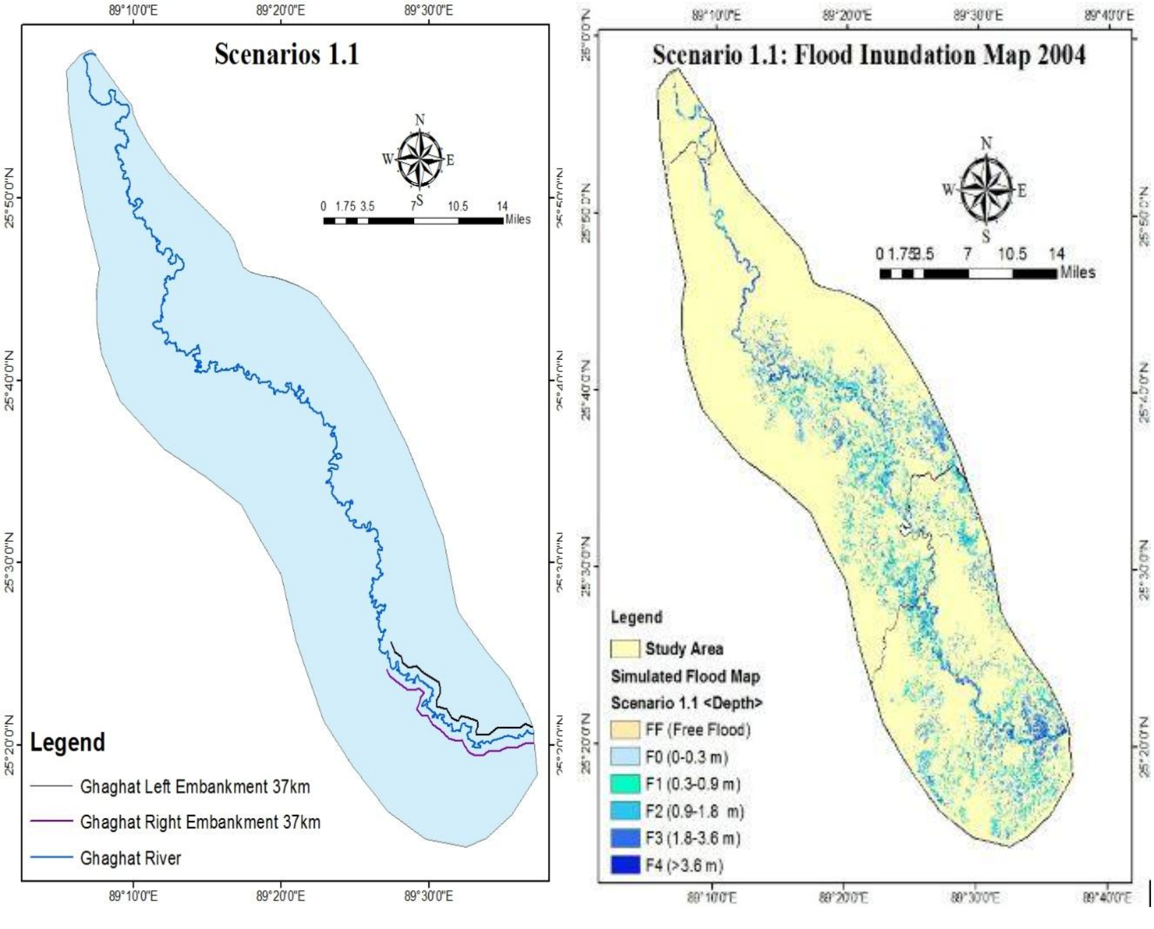

Figure 6.10: Flood Inundation map of 2004 based on Scenario 1.1

After raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream, 237.34 square kilometers have inundated according to the inundation map. This region makes up around 15.49% of the entire study area.

The water level fluctuations due to raising the height of embankment at downstream (scenario 1.1) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 1.1 has been given in figure 6.11.

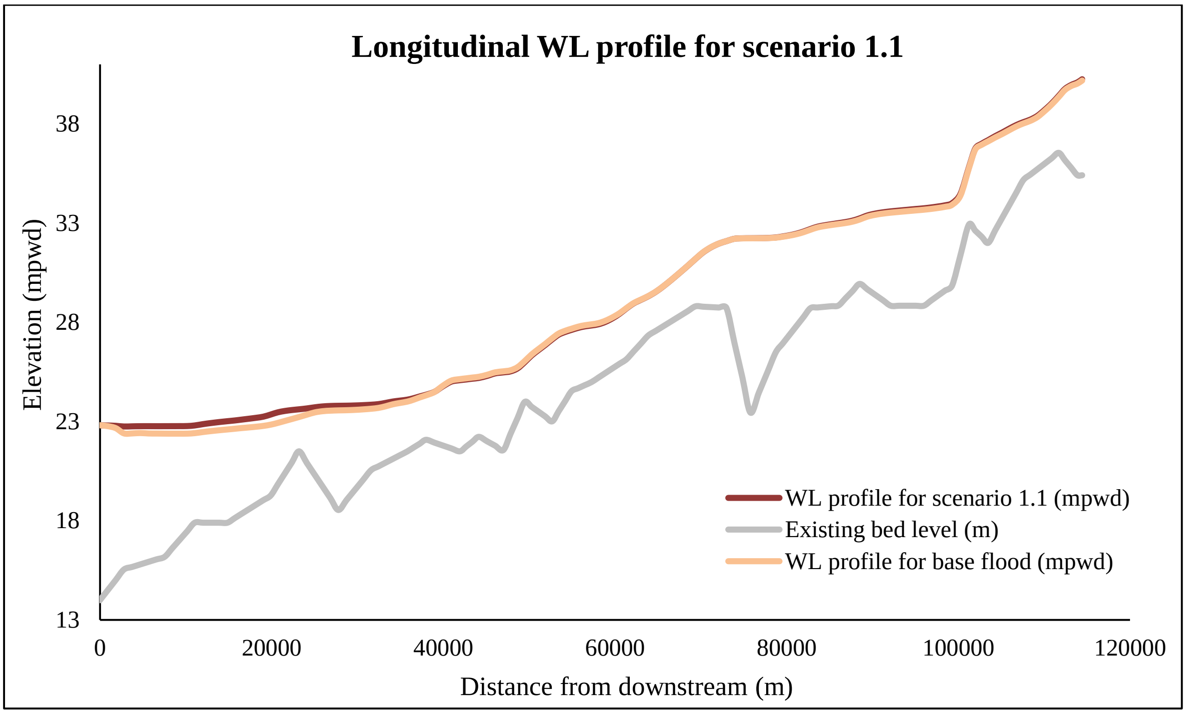

Figure 6.11: Longitudinal WL profile for scenario 1.1

In scenario 1.2, the embankment height is increased by 0.5 meters from its varying existing height 22 to 22.5 meter up to 57 kilometers from downstream in left and right side of the river. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.12.

Scenario 1.2: Raising the existing embankment height by 0.5 meter up to 41.5 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing left bank and right bank from 41.5 kilometers to 57 kilometers and 27.5 kilometers to 57 kilometers respectively.

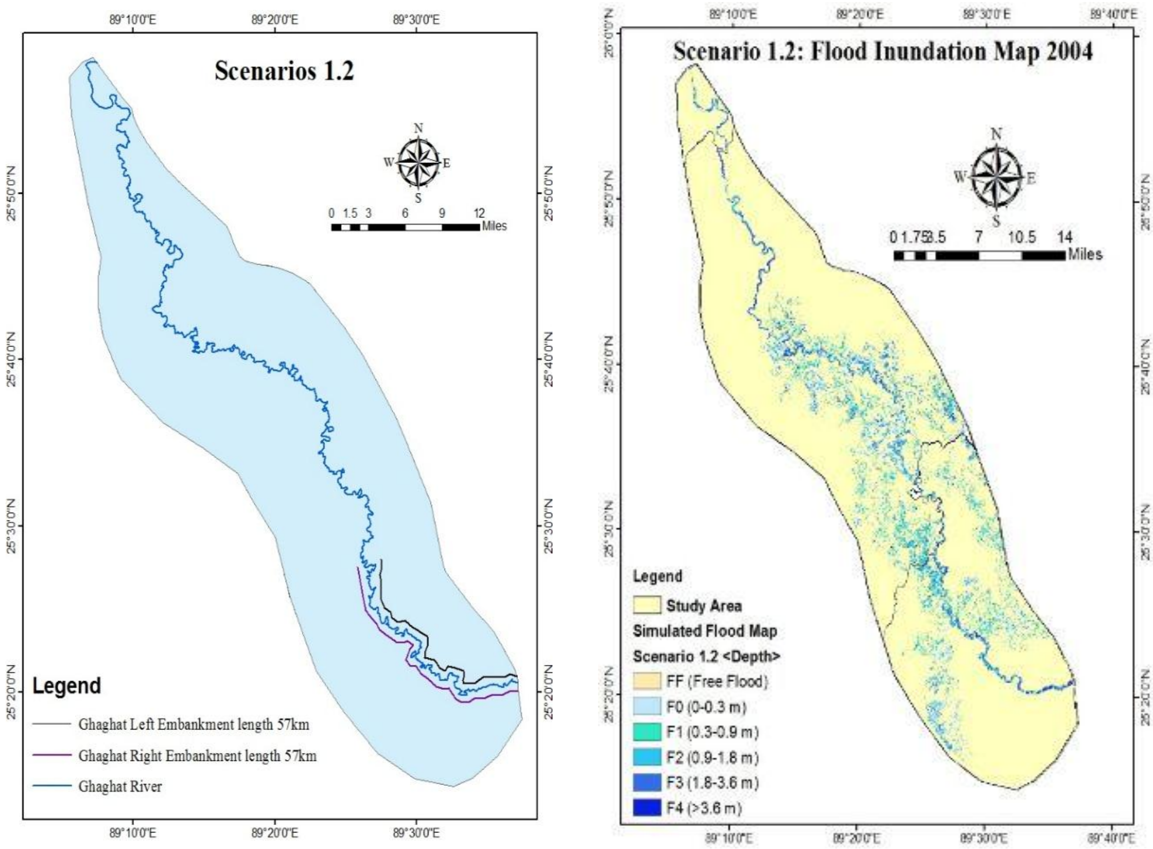

Figure 6.12: Flood Inundation map of 2004 based on Scenario 1.2

After raising the embankment height by 0.5 meter up to 57 kilometers from downstream, 164.74 square kilometers have inundated according to the inundation map. It makes up around 10.75% of the study area. The longitudinal water level profile of Ghaghat River for scenario 1.2 has been given in figure 6.13.

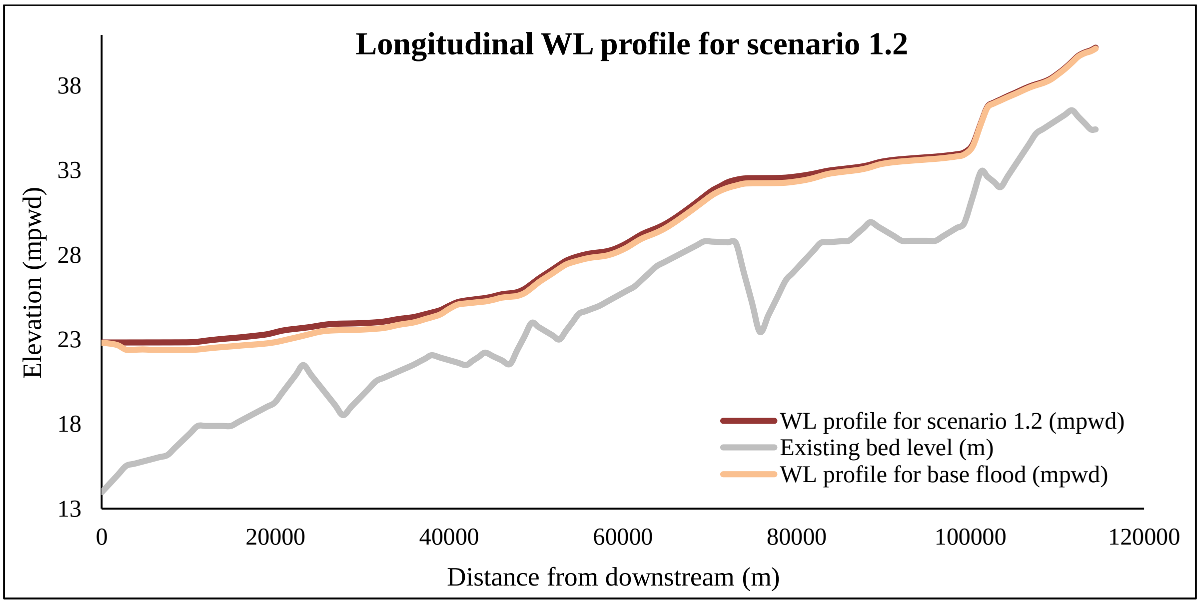

Figure 6.13: Longitudinal WL profile for scenario 1.2

In scenario 1.3, the embankment height has raised by 1 meter up to 37 kilometers and 0.5 meter from 37 kilometers to 57 kilometers from downstream and existing height 22.0 to 23.0 meter up to 37 kilometers and 22.5 to 23.0 meter from 37 kilometers to 57 kilometers downstream in left and right side of the river. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.14.

Scenario 1.3: Raising the existing embankment height by 1 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and 0.5m from 37 kilometers to 41.5 kilometers at left bank and construction of new embankment of 1m height from 27.5 kilometers to 37 kilometers at right bank and construction of new embankment of 0.5m height from existing left bank and right bank from 41.5 kilometers to 57 kilometers and 37 kilometers to 57 kilometers respectively

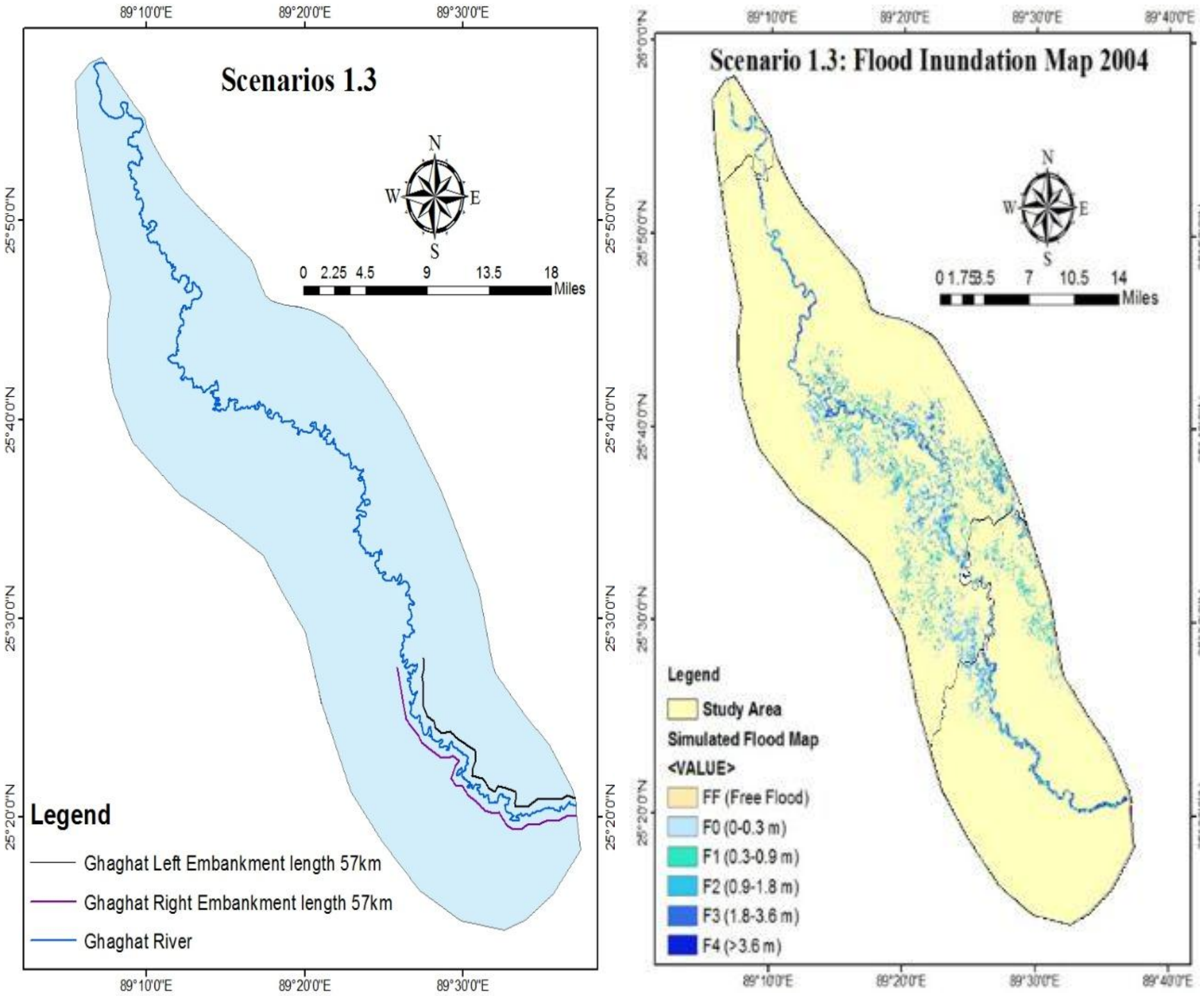

Figure 6.14: Flood Inundation map of 2004 based on Scenario 1.3

After raising the embankment height by 0.5 meter up to 57 kilometers from downstream, 133.58 square kilometers have inundated according to the inundation map. This inundation area covers 8.719% of the study area. The water level fluctuations due to raising the height of embankment and construction of new embankment at downstream (scenario 1.3) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 1.3 has been given in figure 6.15.

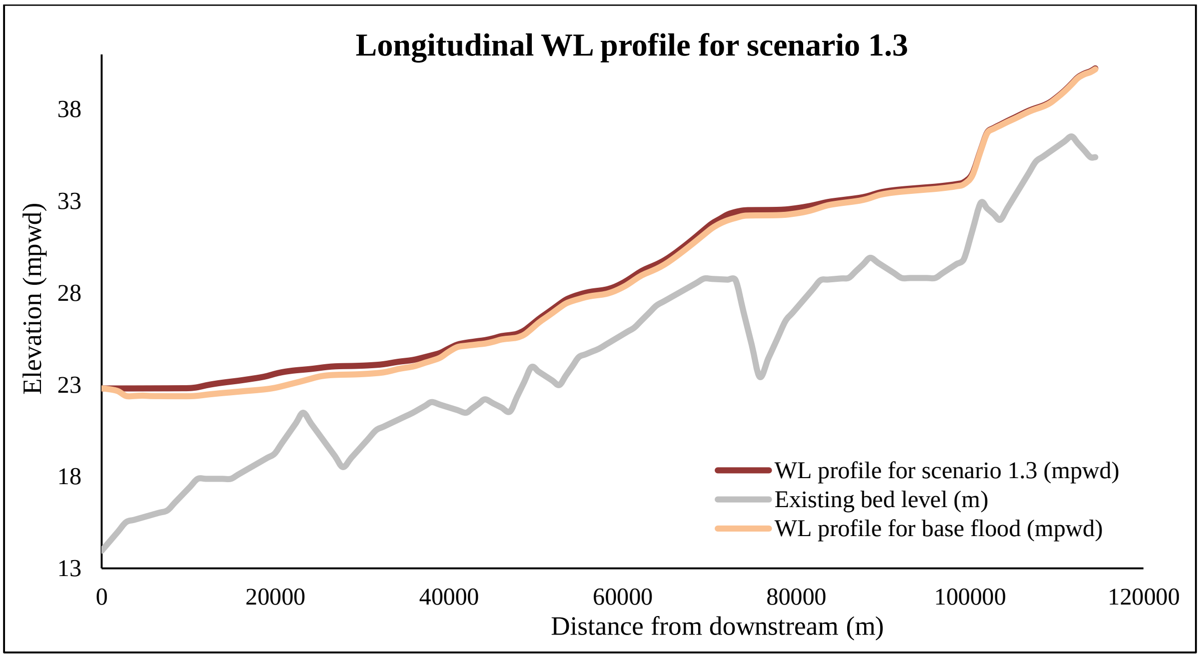

Figure 6.15: Longitudinal WL profile for scenario 1.3

In scenario 1.4, the embankment height has raised by 1.25 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers from downstream at right bank and construction of new embankment of 1.25m height from 27.5 kilometers to 37 kilometers at right bank and construction of new embankment of 1m height from 37 kilometers to 57 kilometers at left and right bank and construction of new embankment of 0.5m height from 57 kilometers to 77 kilometers at left and right bank. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.16.

Scenario 1.4: Raising the existing embankment height by 1.25 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers from downstream at right bank and construction of new embankment of 1.25m height from 27.5 kilometers to 37 kilometers at right bank and construction of new embankment of 1m height from 37 kilometers to 57 kilometers at left and right bank and construction of new embankment of 0.5m height from 57 kilometers to 77 kilometers at left and right bank

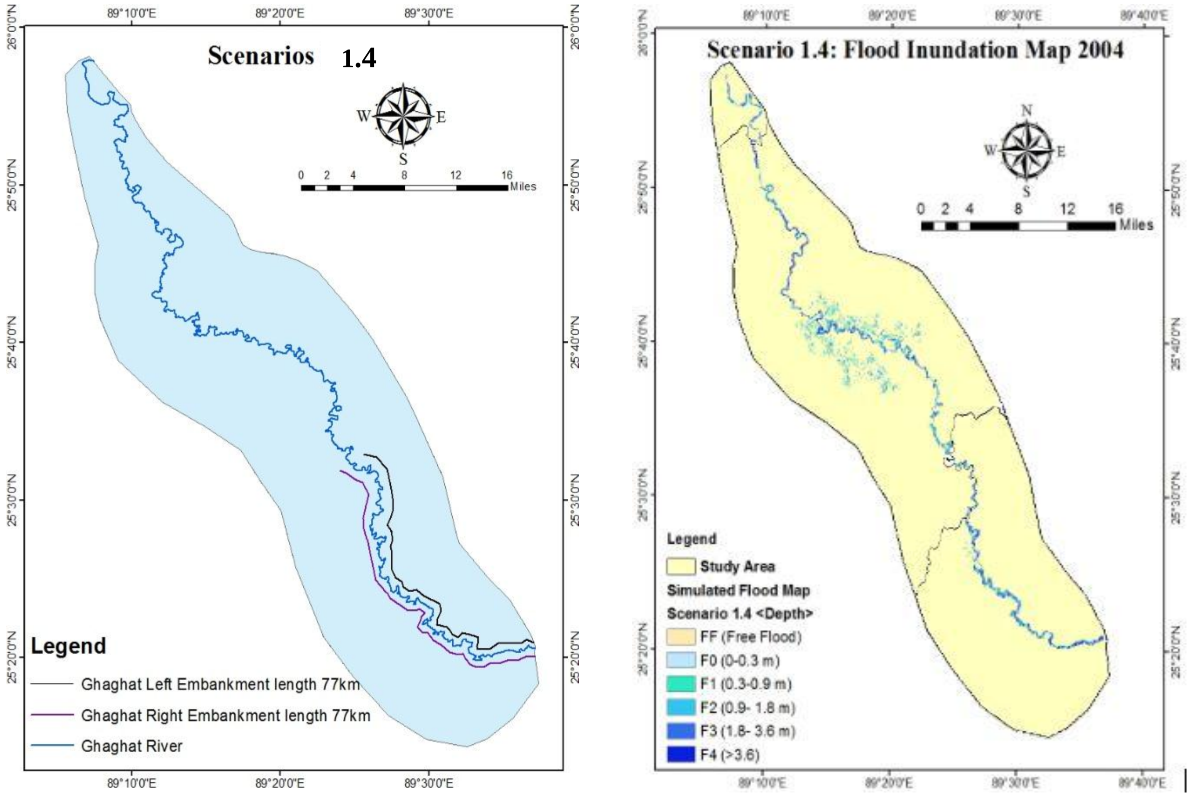

Figure 6.16: Flood Inundation map of 2004 based on Scenario 1.4

After raising 1.25 meters up to 17 kilometers, 1 meter from 37 kilometers to 57 kilometers, and 0.5 meter from 57 kilometers to 77 kilometers, 53.137 square kilometers have inundated according to the inundation map. This inundation map makes up around 3.4% of the research area. The longitudinal water level profile of Ghaghat River for scenario 1.4 has been given in figure 6.17.

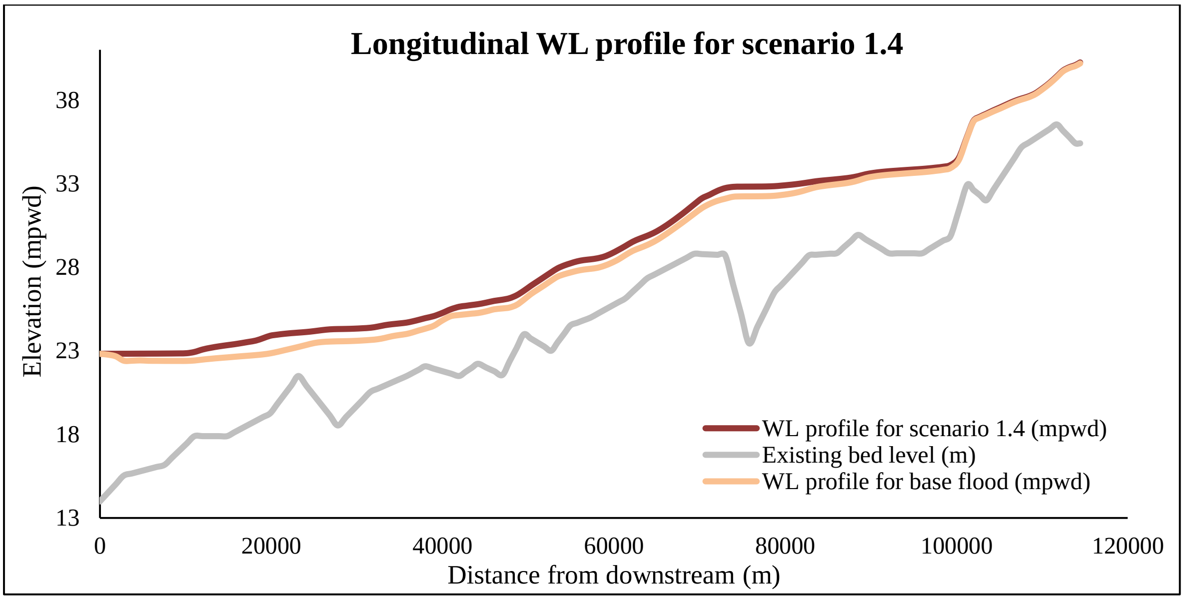

Figure 6.17: Longitudinal WL profile for scenario 1.4

The summary on variation of inundation area and percentage of inundation area in each district for flood years 2004 due to scenario-1 have been represented in table 6.6.

Table 6.6: Inundated area and percentage of Inundated area in particular district and 2004 based on Scenario-1.

Scenario-1	Rangpur			Gaibandha		
	Total Area (sq.km)	**Flood Inundated Area (sq.km)**	**Flood Inundated Area (%)**	**Total Area (sq.km)**	**Flood Inundated Area (sq.km)**	**Flood Inundated Area (%)**
Base Flood	951.759	87.91	9.23	566.422	207.43	36.62
Scenario 1.1		119.86	12.59		117.48	20.74
Scenario 1.2		103.79	10.91		60.95	10.76
Scenario 1.3		102.50	10.77		31.08	5.49
Scenario 1.4		38.15	4.01		13.99	2.47

In Scenario-1, flood inundation area as well as flood depth has been decreased which has been represented by maximum inundated historical event flood map of 2004 in figure 6.10, 6.11, 6.12, 6.14 and 6.16 respectively. From those figures it can be explained that due to extension and increased height of Ghaghat left and right embankment flood inundated area shifted to upward and flood depth of that region reduced gradually.

The maximum flood inundated area has found 119.86 km^2 at Rangpur and 117.48 km^2 at Gaibandha in 2004 which covered about 12.59% and 20.74% of that particular district of the study area in scenario 1.1. In scenario 1.2, maximum flood inundated area has found 103.79 km^2 at Rangpur and 60.95 km^2 at Gaibandha in 2004 which covered about 10.91% and 10.76% of that particular district of the study area. In scenario 1.3, maximum flood inundated area has found 102.50 km^2 at Rangpur and 31.08 km^2 at Gaibandha in 2004 which covered about 10.77% and 5.49% of that particular district of the study area. The minimum flood inundated area has found 38.15km^2 at Rangpur and 13.99 km^2 at Gaibandha in 2004 respectively which covered about 4.01% and 2.47% of that particular district of the study area in scenario 1.4.

From different scenario, significant amount of changes has been observed. The height of embankment has been raised from existing embankment which starts from 0.5m as changes of inundation map are insignificant below 0.5m. For this reason, construction of new embankment has carried out a height start from 0.5m. The water level of Ghaghat River has been changed due to providing embankment in different simulation. The comparison of water level profile of Ghaghat River for scenario 1.1 to 1.4 has been given in figure 6.18.

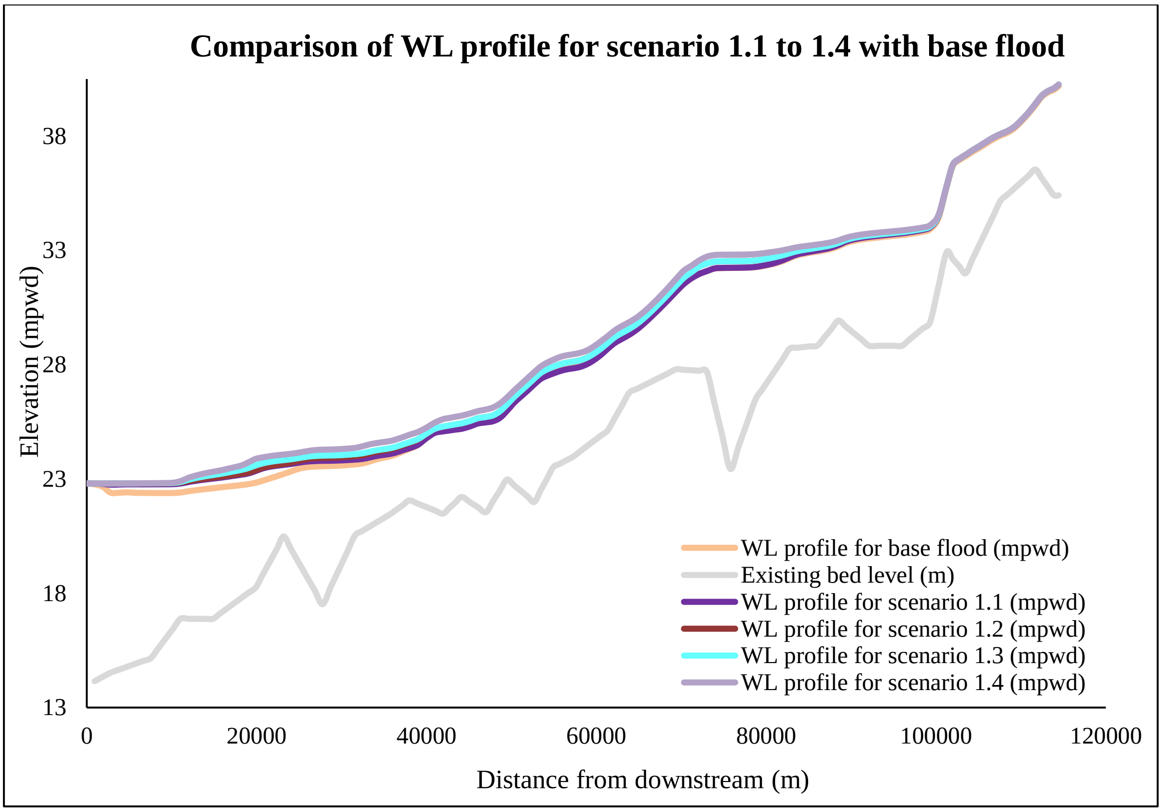

Figure 6.18: Comparison of WL profile for scenario 1.1 to 1.4 with base flood

6.4.2 Dredging

A dredging cross section (channel modification) is used to increase flow carrying capacity of cross sections. In order to perform a channel modification analysis, a hydraulic model of the existing river reaches containing the area in which the channel modification has been analyzed; is developed. Due to lack of flow carrying capacity as was observed this in previous flood inundation map the floodplain of this river has been inundated. It is not practical to dredge the entire course of the river since dredging is expensive from the standpoint of our country.

This model should include several dredging cross sections at downstream and nearest one-third length of Ghaghat River. The proposed option for providing dredging section through Ghaghat River to mitigate flood inundation area are as follows:

Scenario 2.1: Dredging 0.5 meter from the cross-sections 2 to 9 (2.8-31.6 kilometers) and cross-sections 15 to 22 (49.5-73 kilometers)

Scenario 2.2: Dredging 1.0 meter from cross-sections 2 to 9 (2.8-31.6 kilometers) and cross-sections 15 to 22 (49.5-73 kilometers)

Scenario 2.3: Dredging 1.5 meters from the cross-sections 2 to 9 (2.8-31.6 kilometers) and 1.0 meters from the cross-sections 15 to 22 (49.5-73 kilometers)

Figure 6.19 represents the longitudinal bed level profile of Ghaghat River before and after dredging for scenario 2.

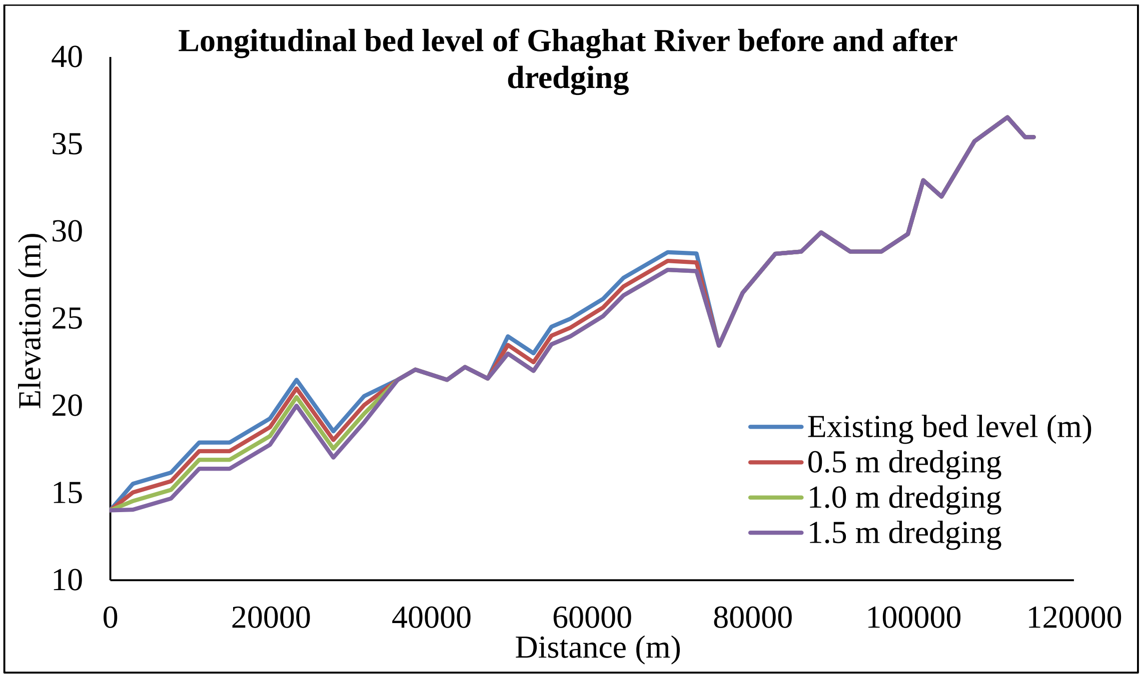

Figure 6.19: Longitudinal bed level profile of Ghaghat River before and after dredging

A typical cross section of Ghaghat River at chainage 46780 has shown in figure 6.20.

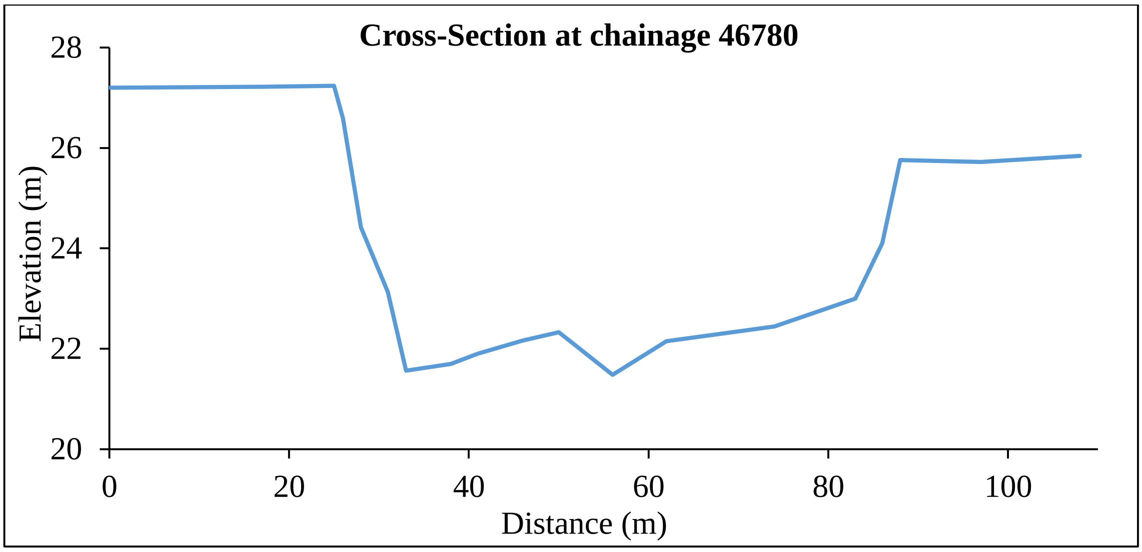

Figure 6.20: Typical cross section of Ghaghat River at chainage 46780

In order to better visualize the improvements made by the dredging works on flood mitigation, a comparison has made between the flooded areas observed in 2004, and those simulated for the same event, but with the current condition, i.e., after completion of the dredging works. At different locations, the riverbed was dredged approximately 0.5 m to 1.5 m. After providing dredging cross-section from the cross-sections 2 to 9 and cross-sections 15 to 22, it has been observed for the analysis of inundation scenarios 2 in the study area for 2004. Model simulated inundation flood map of those particular year are shown in figure 6.21, 6.23 and 6.25. Dredged cross-section for scenario 2.1 to 2.3 has been given in Appendix-A.

In scenario 2.1, a depth of 0.5-meter dredging has provided from the cross-sections 2 to cross-sections 9 with length 2.8 kilometers to 31.6 kilometers i.e. 28.8 kilometers at downstream and cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers i.e. 23.5 kilometers at nearest one-third length of Ghaghat River to protect the floodplain from inundation. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.21.

Scenario 2.1: Dredging 0.5 meter from the cross-sections 2 to 9 (2.8-31.6 kilometers) and cross-sections 15 to 22 (49.5-73 kilometers)

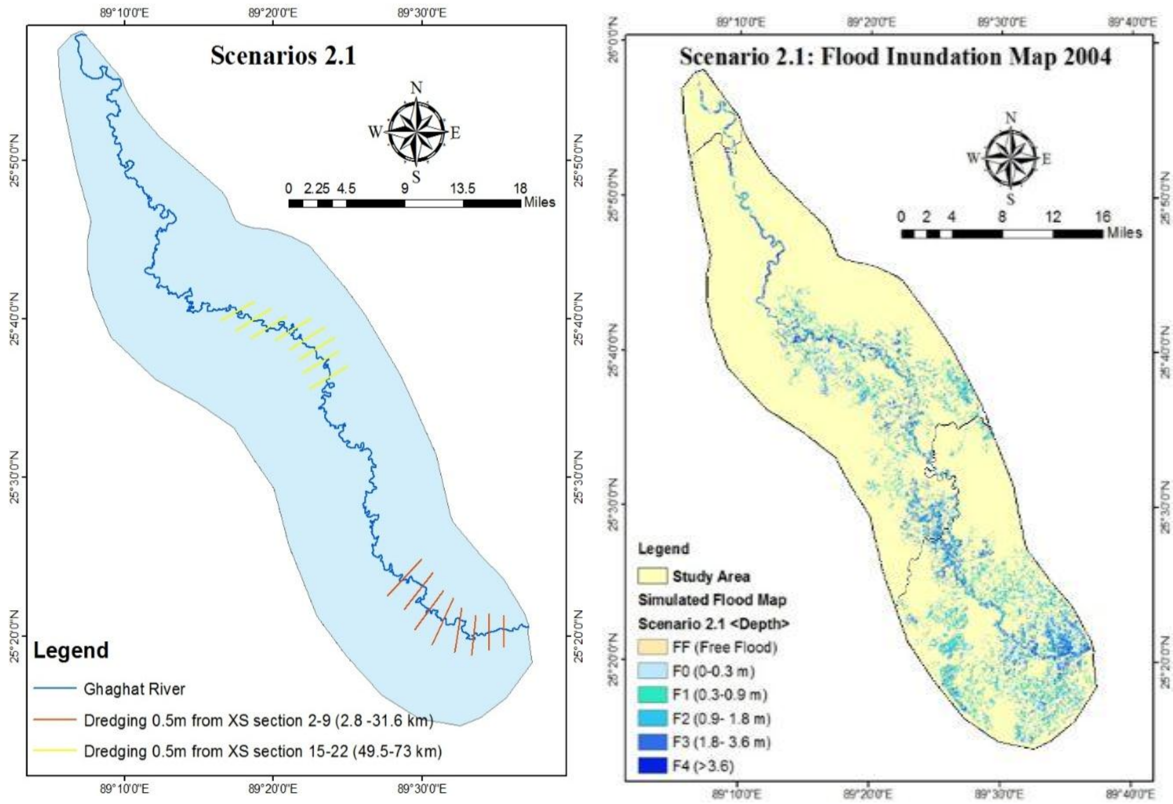

Figure 6.21: Flood Inundation map of 2004 based on Scenario 2.1

After providing dredged section by 0.5 meter from the cross-sections 2 to cross-sections 9 with length 2.8 kilometers to 31.6 kilometers at downstream and cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers, total 222.21 square kilometers area of the study area has been inundated according to the inundation map. This inundation makes up around 14.50% of the research area.

The water level fluctuations due to 0.5m dredging (scenario 2.1) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 2.1 has been given in figure 6.22.

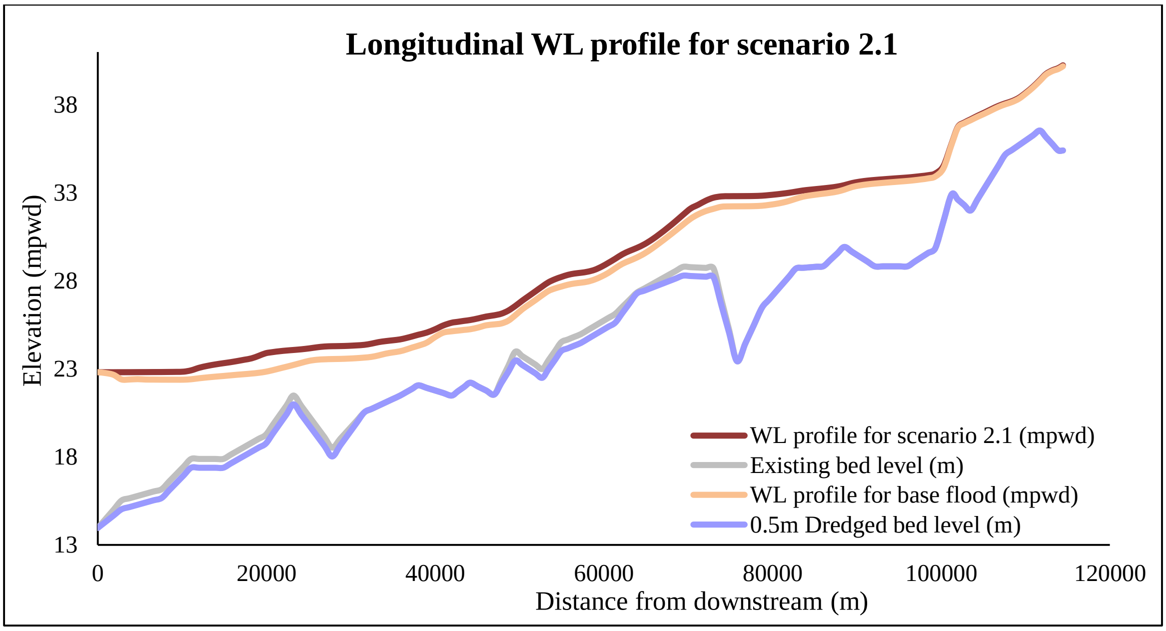

Figure 6.22: Longitudinal WL profile for scenario 2.1

In scenario 2.2, a depth of 1.0-meter dredging has provided from the cross-sections 2 to cross-sections 9 with length 2.8 kilometers to 31.6 kilometers i.e. 28.8 kilometers at downstream and cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers i.e. 23.5 kilometers at nearest one-third length of Ghaghat River to protect the floodplain from inundation. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.23.

Scenarios 2.2: Dredging 1.0 meter from cross-sections 2 to 9 (2.8-31.6 kilometers) and cross-sections 15 to 22 (49.5-73 kilometers)

After providing dredged section by 1.0 meter from the cross-sections 2 to cross-sections 9 with length 2.8 kilometers to 31.6 kilometers at downstream and cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers, total 121.432 km^2 area has been found according to the inundation map. This inundation makes up around 7.93% of the research area.

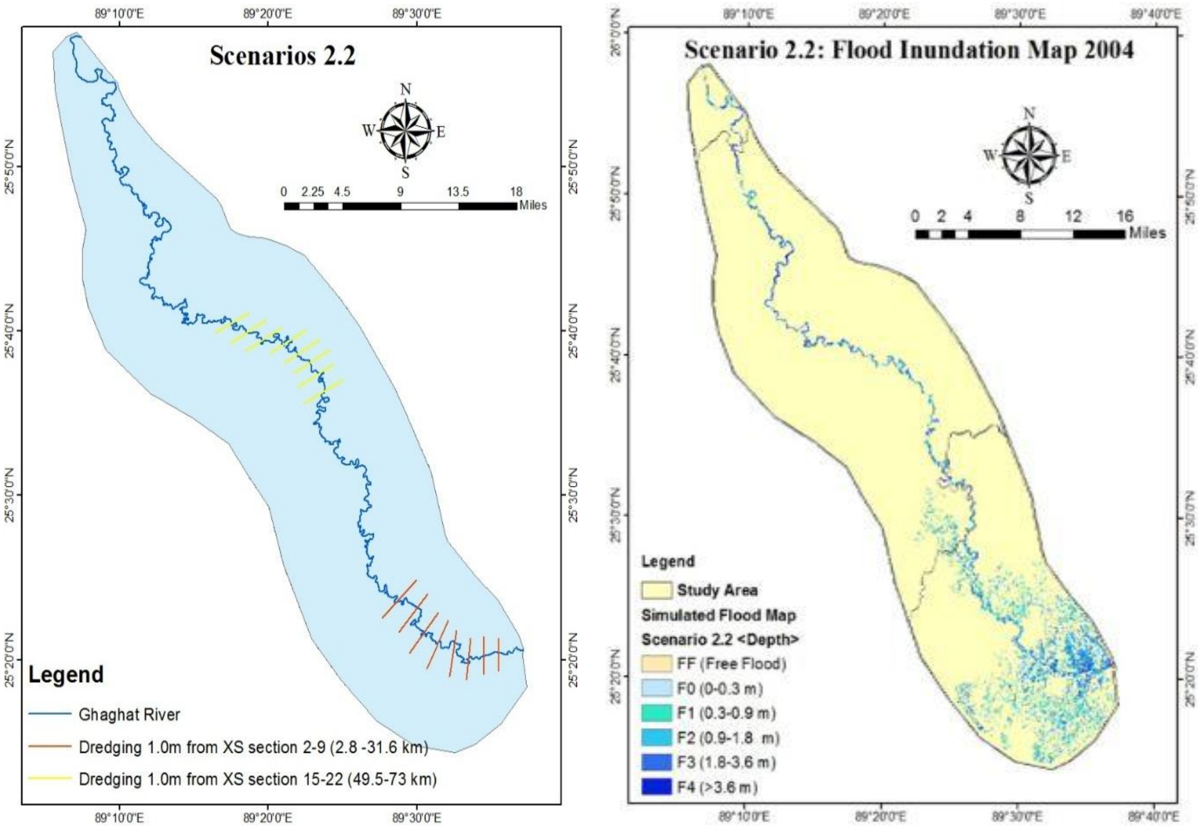

Figure 6.23: Flood Inundation map of 2004 based on Scenario 2.2

The water level fluctuations due to 1m dredging (scenario 2.2) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 2.2 has been given in figure 6.24.

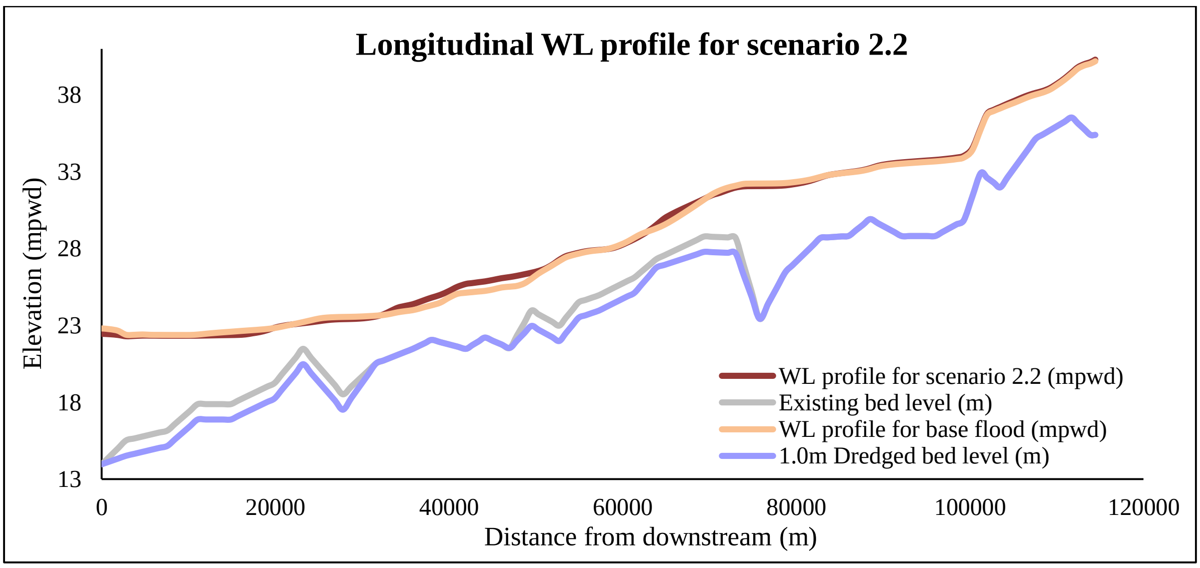

Figure 6.24: Longitudinal WL profile for scenario 2.2

In scenario 2.3, a depth of 1.0-meter dredging has provided from the cross-sections 2 to cross-sections 9 with length 2.8 kilometers to 31.6 kilometers i.e. 28.8 kilometers at downstream and cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers i.e. 23.5 kilometers at nearest one-third length of Ghaghat River to protect the floodplain from inundation. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.25.

Scenarios 2.3: Dredging 1.5 meters from the cross-sections 2 to 9 (2.8-31.6 kilometers) and 1.0 meters from the cross-sections 15 to 22 (49.5-73 kilometers)

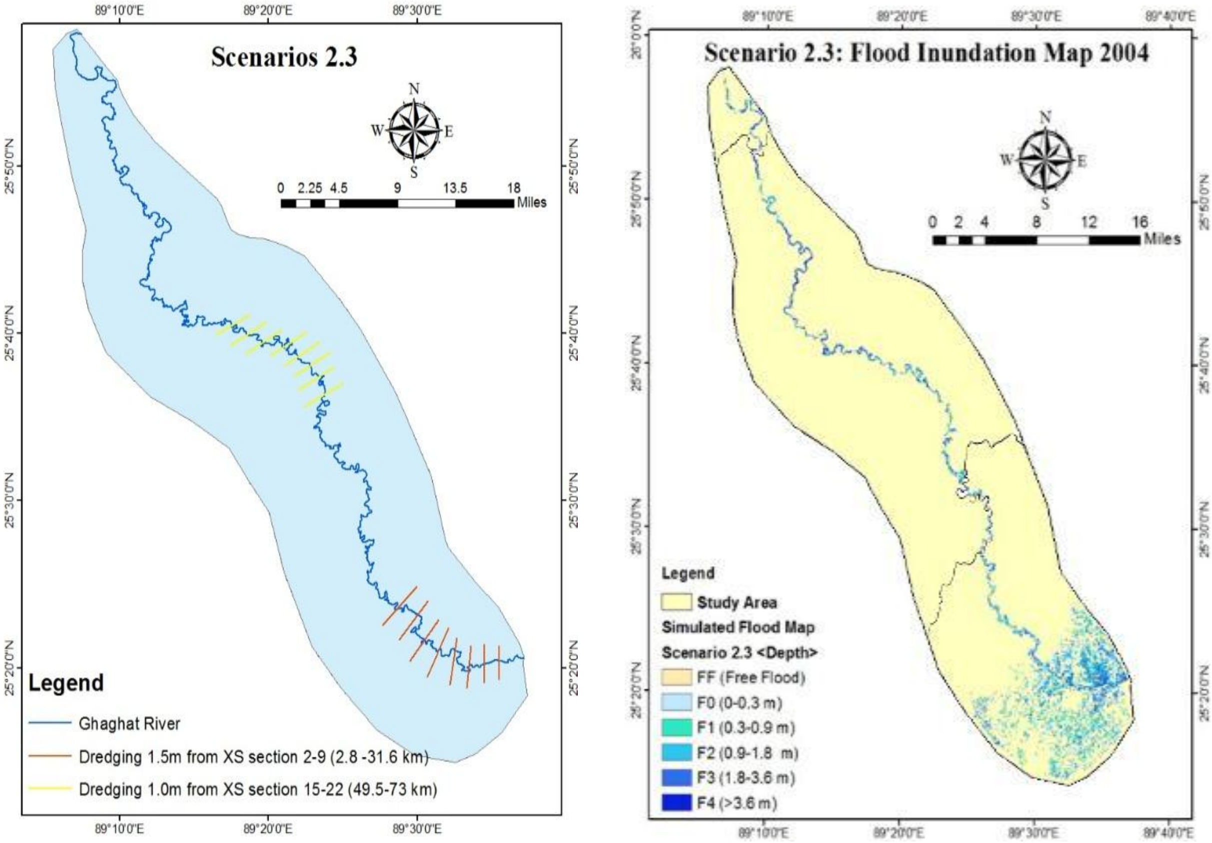

Figure 6.25: Flood Inundation map of 2004 based on Scenario 2.3

After providing dredged section by 1.5 meter from the cross-sections 2 to cross-sections 9 with length 2.8 kilometers to 31.6 kilometers at downstream and dredged section by 1.0 meter cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers, total 106.47 square kilometers area of the study area has been inundated according to the inundation map. This inundation makes up around 6.95% of the research area.

The water level fluctuations due to 1.5m dredging (scenario 2.3) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 2.3 has been given in figure 6.26.

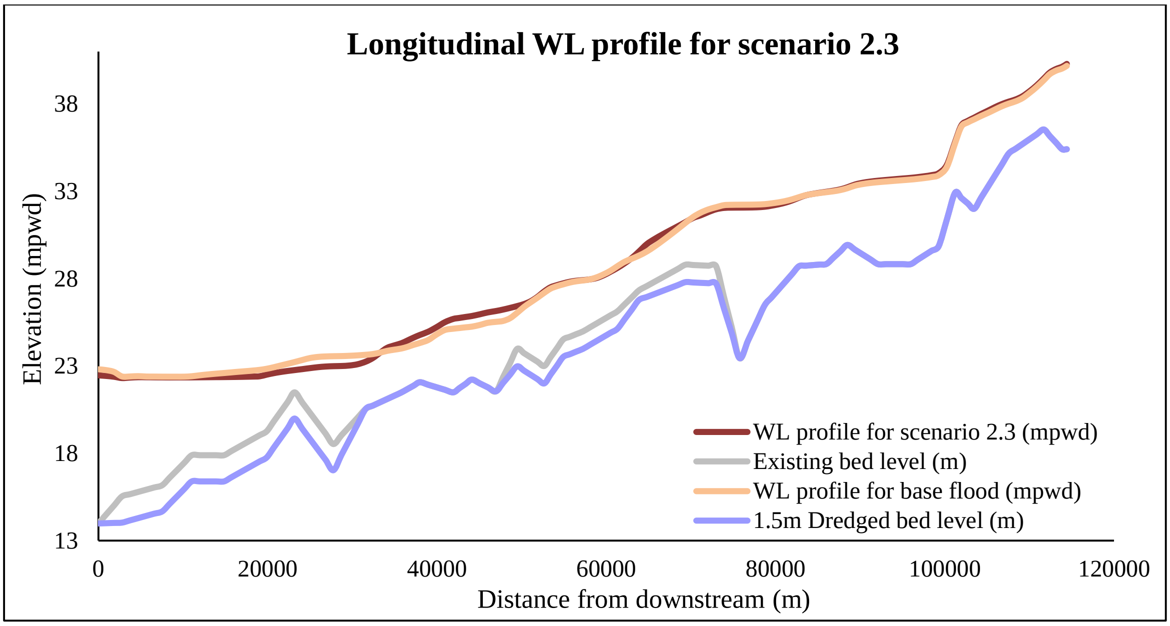

Figure 6.26: Longitudinal WL profile for scenario 2.3

The summary on variation of inundation area and percentage of inundation area in each district for flood years 2004 due to scenario-2 have been represented in table 6.7.

Table 6.7: Inundated area and percentage of Inundated area in particular district in 2004 based on Scenario-2

Scenario-2	**Rangpur**			**Gaibandha**		
	Total Area (sq.km)	**Flood Inundated Area (sq.km)**	**Flood Inundated Area (%)**	**Total Area (sq.km)**	**Flood Inundated Area (sq.km)**	**Flood Inundated Area (%)**
Base Flood	951.759	87.91	9.23	566.422	207.43	36.62
Scenario 2.1		100.13	10.52		122.08	21.55
Scenario 2.2		26.18	2.75		95.26	16.82
Scenario 2.3		21.88	2.30		84.59	14.93

The maximum flood inundated area has found 122.08 km^2 at Rangpur and 100.13 km^2 at Gaibandha in 2004 which covered about 21.55% and 10.52% of that particular district of the study area in scenario 2.1. In scenario 2.2, maximum flood inundated area has found 26.18 km^2 at Rangpur and 95.26 km^2 at Gaibandha in 2004 respectively which covered about 2.75% and 16.82% of that particular district of the study area. In scenario 2.3, minimum flood inundated area has found 21.88 km^2 at Rangpur and 84.59 km^2 at Gaibandha in 2004 respectively which covered about 2.30% and 14.93% of that particular district of the study area.

The water level of Ghaghat River has been changed with respect to existing bed level at different location due to providing dredging section in scenario 2. The comparison of water level profile of Ghaghat River for scenario 2.1 to 2.3 has been given in figure 6.27.

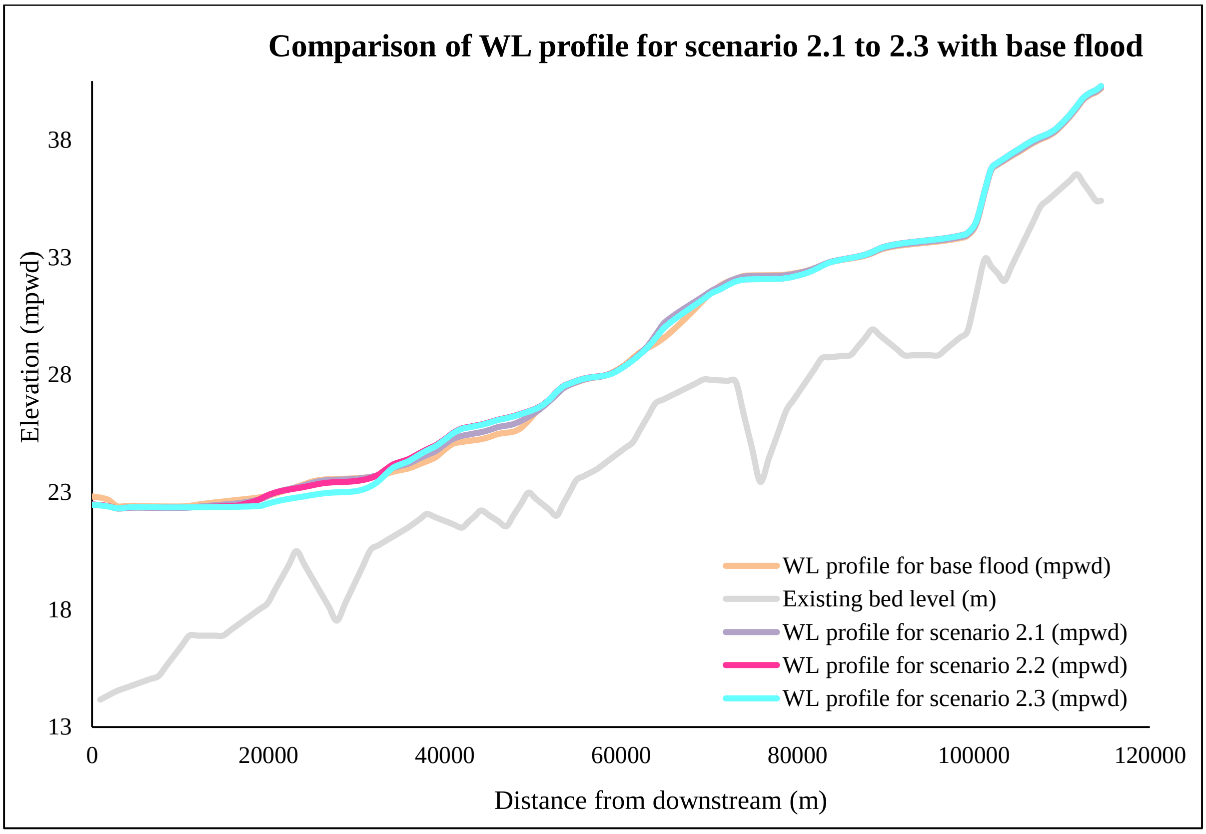

Figure 6.27: Comparison of WL profile for scenario 2.1 to 2.3 with base flood

6.4.3 Combination of Embankment and Dredging

As extension of Ghaghat left and right embankment as well as raising height of embankment has able to reduce a major percentage of inundated area but lack of floodplain inundation reduces transmission loss and groundwater recharge, thereby severely affecting the groundwater resources and their associated ecological and economic benefits. This has consequences on base flow-groundwater interactions and degrades riverine habitats. Floodwater spreading onto the flood plains improves soil fertility by depositing silt, exchanging nutrients and carbon between flood plain and channel, creating new habitats, reinstating floodplain refuges and spawning areas for river species. Embankments reduce floodplain fertility because sediments and their nutrients are no longer deposited and exchanged. On the other hand, only dredging section has not been capable to provide enough area to decrease inundation area. That’s why a combination of Embankment and Dredging section would be provided at the same time in scenario-3.

In this scenario, combination of Embankment and Dredging section from upstream would meet together which formed the following options to mitigate flood inundation.

Scenario 3.1: Raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and Dredging 0.5 meter from cross-sections 15 to 22 (49.5-73 kilometers)

Scenario 3.2: Raising the existing embankment height by 1 meter up to 20 kilometers from downstream at left bank and right bank and raising the existing embankment height by 1.2 meter from 20 kilometers to 37 kilometers from downstream at left bank and from 20 kilometers to 27.5 kilometers at right bank and construction of new embankment of 1.2m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and Dredging 1.0 meter from cross-sections 15 to 22 (49.5-73 kilometers)

In scenario 3.1, the embankment height is raised by 0.5 meters from its varying existing height 22 to 22.5 meter up to 37 kilometers from downstream in left and right side of the river as well as a depth of 0.5-meter dredging has provided from the cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers i.e. 23.5 kilometers at nearest one-third length of Ghaghat River to protect the floodplain from inundation. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results shown in figure 6.28.

Scenario 3.1: Raising the existing embankment height by 0.5 meter up to 37 kilometers from downstream at left bank and 27.5 kilometers at right bank and construction of new embankment of 0.5m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and Dredging 0.5 meter from cross-sections 15 to 22 (49.5-73 kilometers)

After raising the embankment height by 0.5 meter up to 57 kilometers from downstream, and providing dredged section by 0.5 meter from the cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers, total 194.47 square kilometers area has been inundated according to the inundation map. This inundation makes up around 12.69% of the research area.

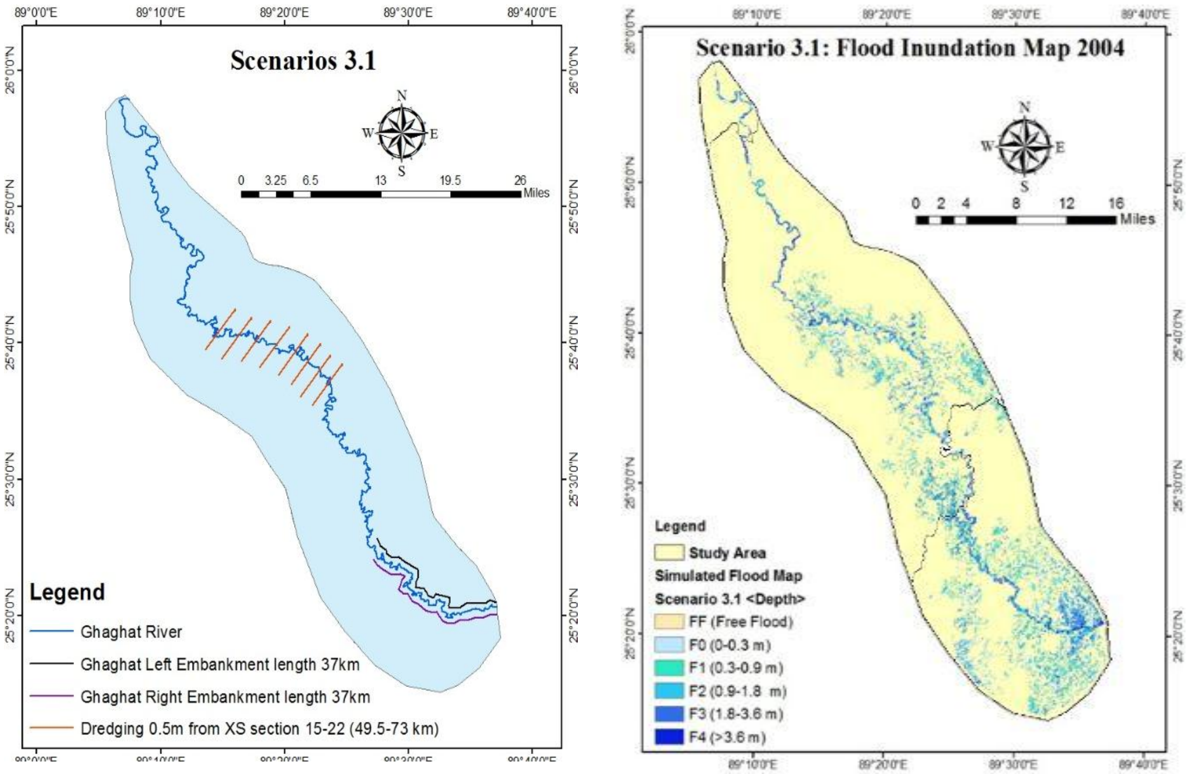

Figure 6.28: Flood Inundation map of 2004 based on Scenario 3.1

The water level fluctuations due to raising height of embankment as well as 0.5m dredging (scenario 3.1) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 3.1 has been given in figure 6.29.

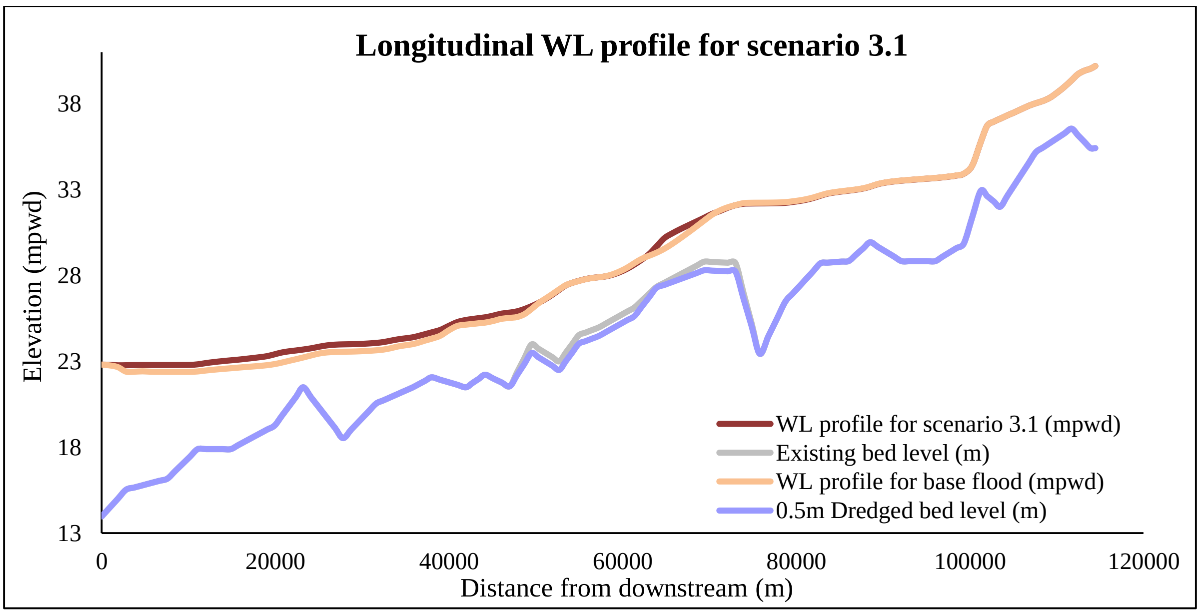

Figure 6.29: Longitudinal WL profile for scenario 3.1

In scenario 3.2, the embankment height is raised by 1.0 meters from its varying existing height 22 to 23meter up to 20 kilometers, 1.2 meters from its varying existing height 22 to 23.2 meter from 20 kilometers to 37 kilometers, from downstream in left and right side of the river also a depth of 1.0-meter dredging has provided from cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers i.e. 23.5 kilometers at nearest one-third length of Ghaghat River to protect the floodplain from inundation. Then this change is incorporated in HEC-RAS 1D/2D couple model after that the following map results represented in figure 6.30.

Scenario 3.2: Raising the existing embankment height by 1 meter up to 20 kilometers from downstream at left bank and right bank and raising the existing embankment height by 1.2 meter from 20 kilometers to 37 kilometers from downstream at left bank and from 20 kilometers to 27.5 kilometers at right bank and construction of new embankment of 1.2m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and Dredging 1.0 meter from cross-sections 15 to 22 (49.5-73 kilometers)

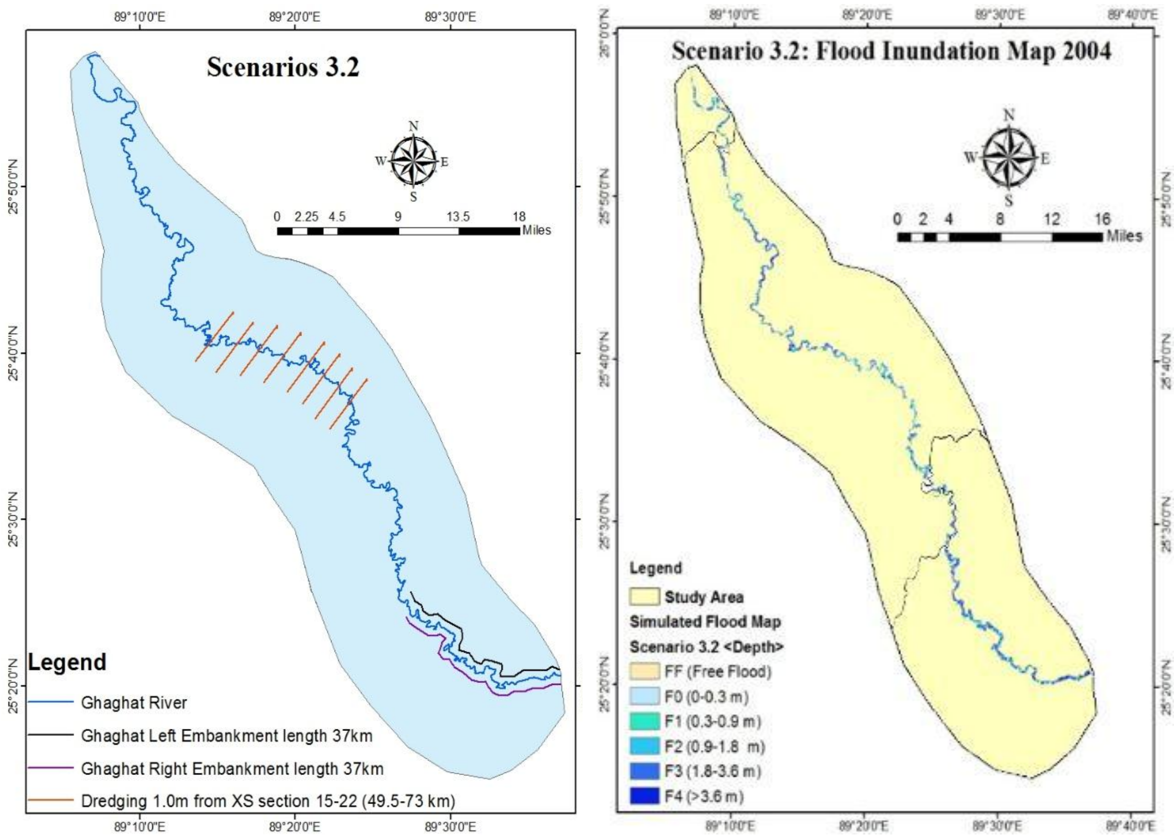

Figure 6.30: Flood Inundation map of 2004 based on Scenario 3.2

After raising the embankment height by 1.0 meter to 20 kilometers, 1.2 meters from 20 kilometers to 37 kilometers downstream, and providing dredged section by 1.0 meter from the cross-sections 15 to cross-sections 22 with length of 49.5 kilometers to 73 kilometers, total 35.29 square kilometers area has been inundated according to the inundation map. This inundation makes up around 2.30% of the research area.

The water level fluctuations due to raising height of embankment as well as 1.0m dredging (scenario 3.2) along the river has been generated after simulation. The longitudinal water level profile of Ghaghat River for scenario 3.2 has been given in figure 6.31.

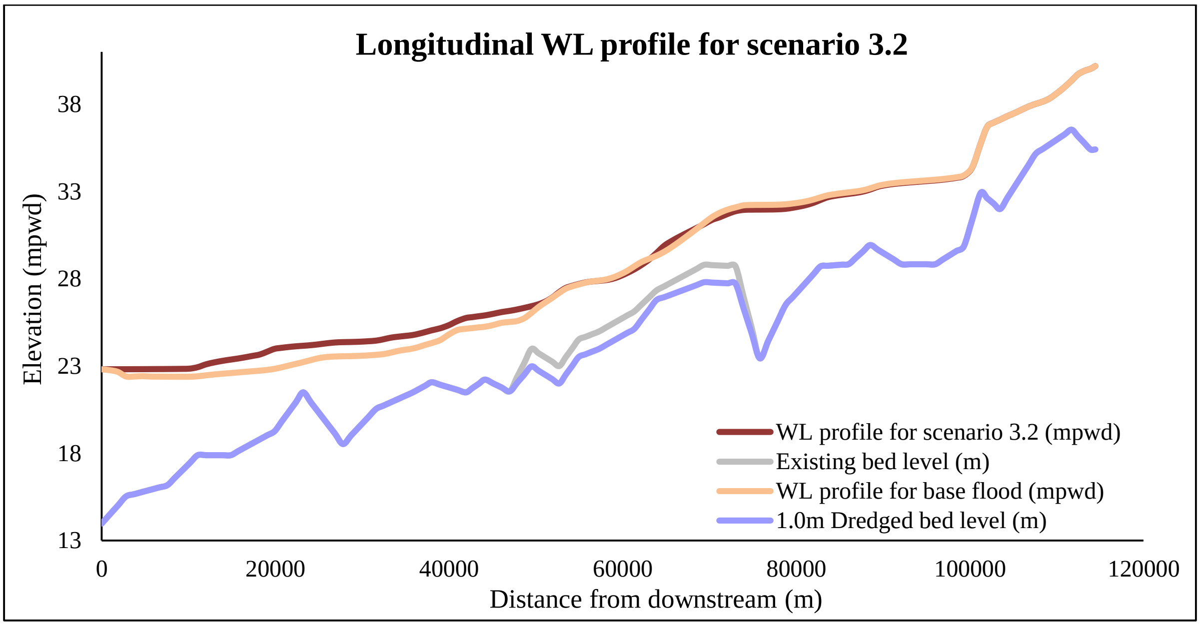

Figure 6.31: Longitudinal WL profile for scenario 3.2

The summary of the Inundated area and percentage of Inundated area in particular district in 2004 based on Scenario-3 have been represented in table 6.8.

Table 6.8: Inundated area and percentage of Inundated area in particular district in 2004 based on Scenario-3

Scenario-3	**Rangpur**			**Gaibandha**		
	Total Area (sq.km)	**Flood Inundated Area (sq.km)**	**Flood Inundated Area (%)**	**Total Area (sq.km)**	**Flood Inundated Area (sq.km)**	**Flood Inundated Area (%)**
Base Flood	951.759	87.91	9.23	566.422	207.43	36.62
Scenario 3.1		89.08	9.36		105.40	18.61
Scenario 3.2		21.75	2.28		13.55	2.39

The maximum flood inundated area has found 89.08 km^2 at Rangpur and 105.40 km^2 at Gaibandha in 2004 which covered about 9.36% and 18.61% of that particular district of the study area in scenario 3.1. In scenario 3.2, maximum flood inundated area has found 21.75 km^2 at Rangpur and 13.55km^2 at Gaibandha in 2004 respectively which covered about 2.28% and 2.39% of that particular district of the study area.

The model was simulated by introducing three countermeasures (Embankment, Dredging, Combination of Embankment and Dredging) for 2004. The inundation area reduced from 295.34 km^2 to 21.75 km^2 and the percentage of reduction was around 19.27% to 2.28%. Also, it showed considerable reduction in inundation areas and affected people with the introduction of three option.

The water level of Ghaghat River has been changed due to providing embankment and dredging section in scenario 3. The comparison of water level profile of Ghaghat River for scenario 3.1 to 3.2 has been given in figure 6.32.

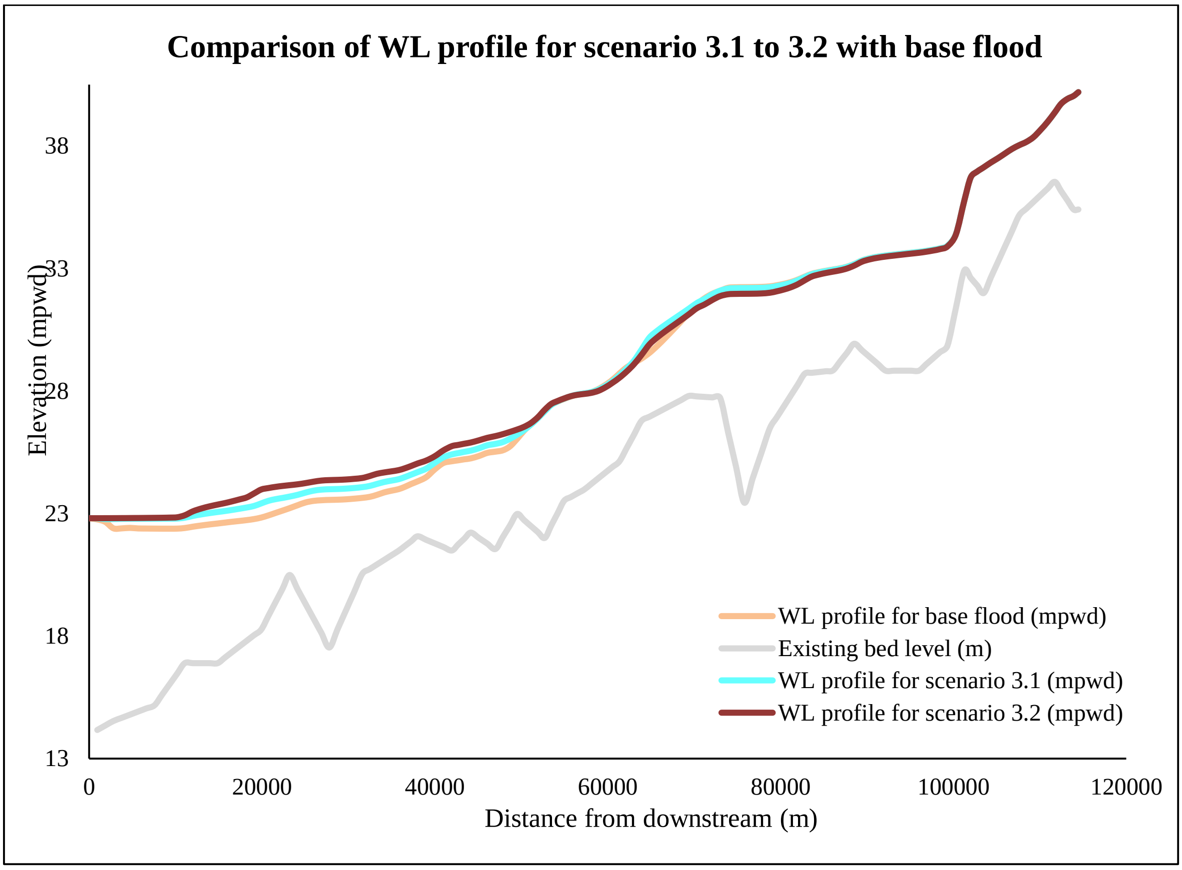

Figure 6.32: Comparison of WL profile for scenario 3.1 to 3.2 with base flood

For comparison of water level, ten locations have been selected shown in figure 6.33. The comparison of water level at ten different locations for scenario 1.1 to 3.2 have been represented in table 6.9.

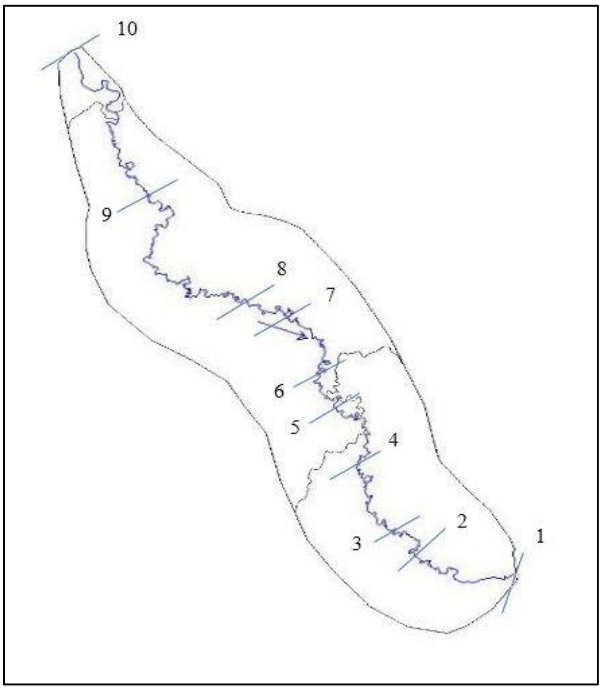

Figure 6.33: Ten selected location for water level comparison

Table 6.9: Comparison of water level at different location for scenario 1.1 to 3.2

Location no.	Distance from downstream (m)	WL (m pwd)									
		Base flood	For S-1.1	For S-1.2	For S-1.3	For S-1.4	For S-2.1	For S-2.2	For S-2.3	For S-3.1	For S-3.2
1	0	22.81	22.81	22.81	22.81	22.81	22.47	22.47	22.47	22.81	22.81
2	19900	22.84	23.36	23.40	23.60	23.89	22.83	22.86	22.51	23.41	23.98
3	26867	23.54	23.79	23.91	24.01	24.27	23.51	23.40	22.98	23.97	24.35
4	42683	25.17	25.12	25.34	25.35	25.68	25.45	25.77	25.76	25.46	25.80
5	56505	27.85	27.80	28.09	28.09	28.42	27.86	27.89	27.89	27.86	27.84
6	64817	29.55	29.55	29.80	29.80	30.08	30.18	29.98	29.98	30.18	29.90
7	73933	32.21	32.21	32.51	32.51	32.80	32.18	32.05	32.05	32.18	31.95
8	78750	32.27	32.28	32.56	32.56	32.84	32.24	32.12	32.12	32.23	32.01
9	99300	33.92	34.01	34.05	34.05	34.10	33.97	34.04	34.04	33.92	33.89
10	114450	40.19	40.25	40.25	40.25	40.25	40.23	40.29	40.29	40.19	40.19

The summary of the comparison of all scenarios of flood mitigation with base flood 2004 has been represented in figure 6.34, 6.35 and 6.36 respectively.

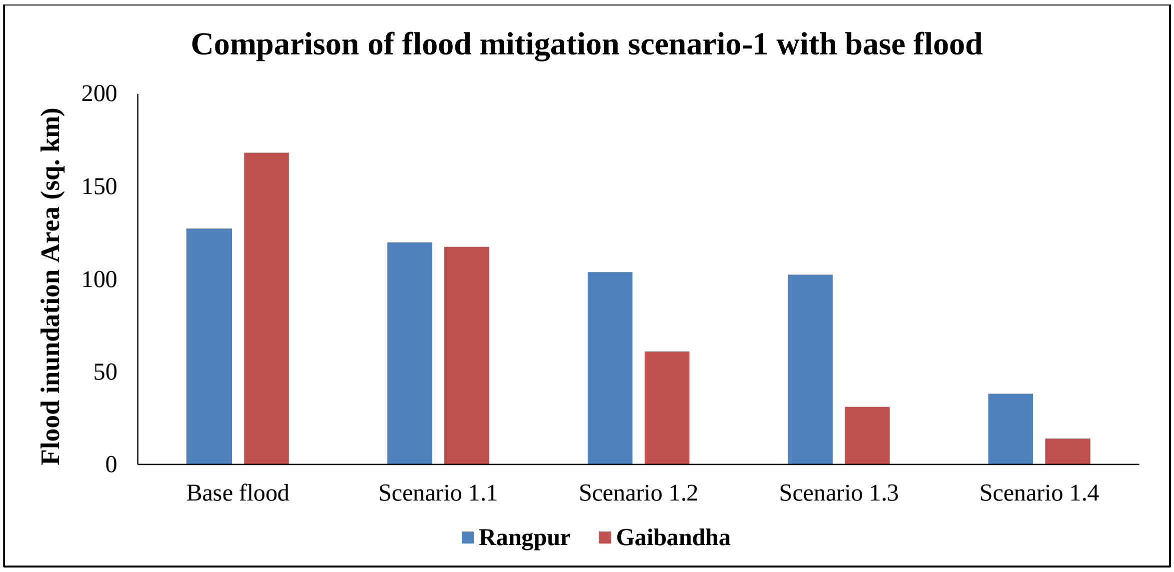

Figure 6.34: Comparison of flood mitigation scenario-1 with base flood

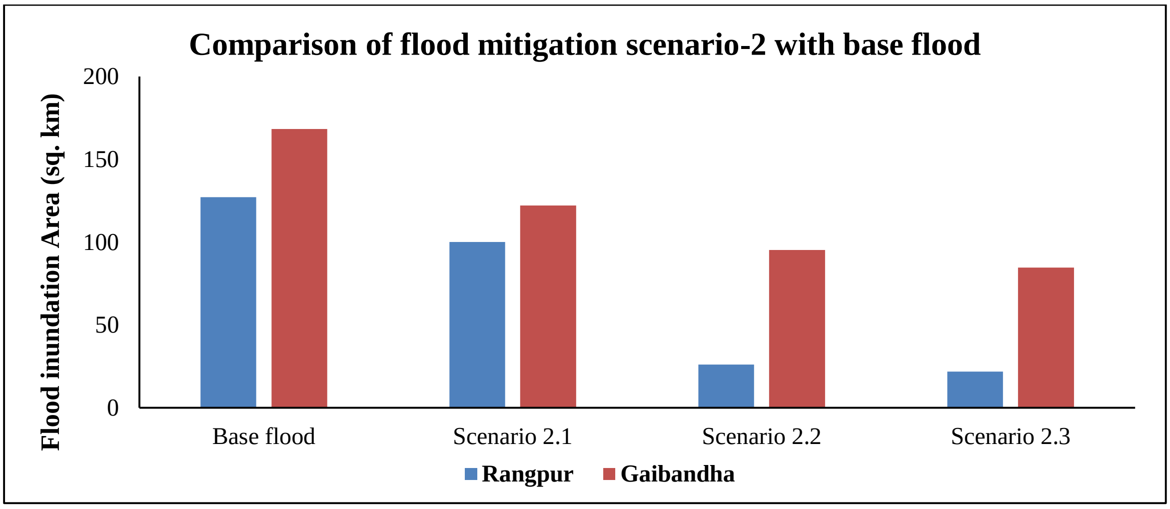

Figure 6.35: Comparison of flood mitigation scenario-2 with base flood

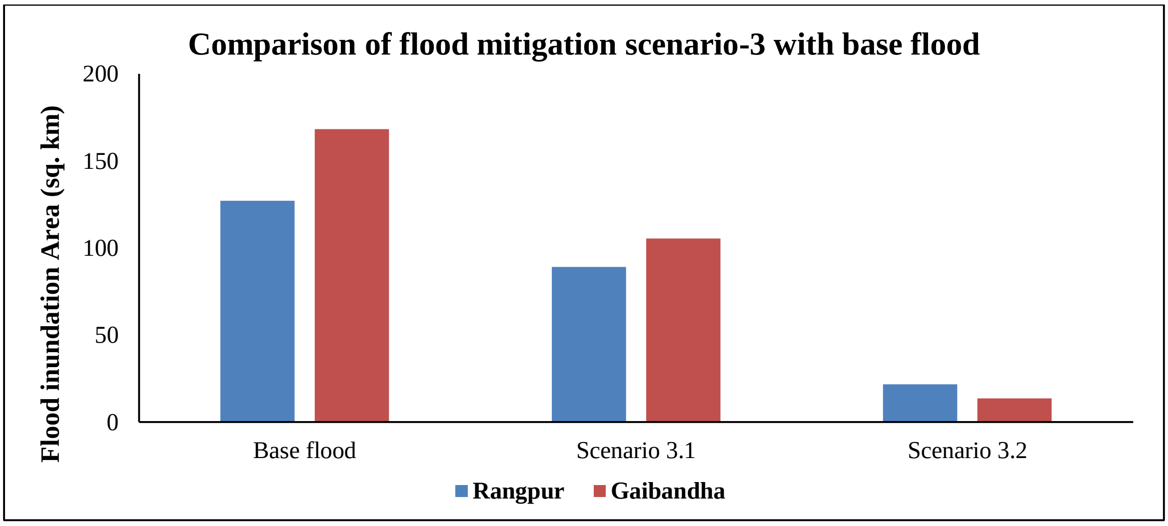

Figure 6.36: Comparison of flood mitigation scenario-3 with base flood

The summary of the percentage of all scenarios of flood mitigation have been represented in table 6.10 and figure 6.37.

Table 6.10: Percentage of flood inundated area from flood mitigation Scenarios 1.1-3.2

Flood Mitigation Scenarios	Flood Inundated Area (sq.km)	Flood Inundated Area (%)
Base Flood	295.34	19.28
Scenario 1.1	237.34	15.49
Scenario 1.2	164.74	10.75
Scenario 1.3	133.58	8.72
Scenario 1.4	52.137	3.40
Scenario 2.1	222.21	14.50
Scenario 2.2	121.43	7.93
Scenario 2.3	106.47	6.95
Scenario 3.1	194.47	12.69
Scenario 3.2	35.30	2.30

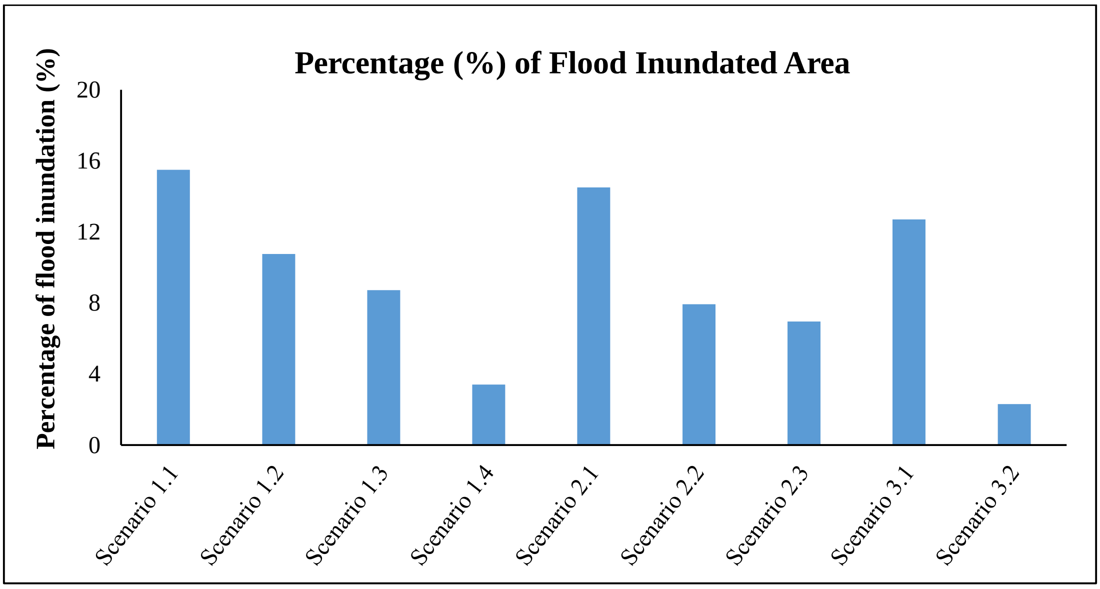

Figure 6.37: Results of percentage of inundated area from flood mitigation scenarios

6.5 Cost Estimation for flood mitigation scenarios

For flood mitigation scenarios, costing is one of the most important parts. In which, the implementation of whole project depends on either it has to be economical or expensive. In order to determine the viability of a project before it started, cost analysis can be used. Three scenarios and their corresponding sub-scenarios has been used in this research project as a trial option for mitigation of flood inundation. These costs do not include allowances and contingencies for design, construction management, permitting, mobilization, unscheduled items, and changed conditions. Quantity estimating portions of the model are based on geometric equations that are to allow for updating of the overall cost estimates should some of the dimensions of the embankments change.

Earthwork filling work in any type of embankment with suitable dredged soil collected from silt-up river/canal bed by dredging with appropriate local dredger, including carrying through pipe or any other suitable means, loading, unloading and filling gradually at the right place of filling area in an artificial silt up manner at a suitable height and distance, including leveling, dressing and all necessary arrangements to fill up soil and compacting to 95% minimum dry density at optimum moisture content. Rates is inclusive of cost of all materials, their carriages, hire charges of dredger and all other machines, equipment for filling soil as per specification, fuel, lubricants and all incidental charges in this connection etc. Bangladesh water development board (BWDB), Local Government Engineering Department (LGED) and some other organization published their schedule rates for different types of construction work. The cost of per cumec volume of earthwork up to 1.5m initial lift from toe of the embankment including 95% compaction of distance more than 4km is approximately 500Tk. According to BWDB Dredging cost is 150 Tk. per cumec (BWDB Schedule of Rates - Volume-1). Therefore, cost estimates for all circumstances have been shown in table 6.11, 6.12, 6.13, 6.14, 6.15 and 6.16 respectively.

Table 6.11: Cost Estimation for flood mitigation Scenarios 1

Scenarios	Embankment height (m)	Area (meter square)	Length (km)	Volume (cumec)	Cost per cumec According to BWDB (Tk.)	Total Cost (Crore Tk.)	Total Cost for embankment on both side (Crore Tk.)
Scenario 1.1	0.5	2	37	74000	500	3.7	7.4
Scenario 1.2	0.5	2	57	114000	500	5.7	11.4
Scenario 1.3	1	5	57	225000	500	11.25	22.5
Scenario 1.4	1.25	6.87	77	362400	500	18.12	36.24

Table 6.12: Cost Estimation for flood mitigation Scenario 2.1

Cross Section	Area (m^2) for 0.5m dredging	Length (m)	Volume (cumec)	Dredging Cost per cumec According to BWDB (Tk.)	Total cost (Crore Tk.)
2	65	2800	182000	150	2.73
3	47.75	4750	226812.5	150	3.40
4	63	3500	220500	150	3.30
5	86.625	3807	329781.375	150	4.94
6	91.5	5043	461434.5	150	6.92
7	70.25	3300	231825	150	3.47
8	104	4584	476736	150	7.15
15	29	2500	72500	150	1.08
16	27.25	3200	87200	150	1.30
17	100.75	2250	226687.5	150	3.40
18	34	2332	79288	150	1.18
19	19	4068	77292	150	1.15
20	31	2550	79050	150	1.18
21	17.75	5500	97625	150	1.46
22	62.25	3600	224100	150	3.36
				Total	46.02

Table 6.13: Cost Estimation for flood mitigation Scenario 2.2

Cross Section	Area(m^2) for 1.0m dredging	Length(m)	Volume (cumec)	Dredging Cost per cumec According to BWDB (Tk.)	Total cost (Crore Tk.)
2	130	2800	364000	150	5.46
3	95.5	4750	453625	150	6.80
4	126	3500	441000	150	6.62
5	188.5	3807	717619.5	150	10.76
6	183	5043	922869	150	13.84
7	140.5	3300	463650	150	6.95
8	208	4584	953472	150	14.30
15	58	2500	145000	150	2.18
16	54.5	3200	174400	150	2.62
17	201.5	2250	453375	150	6.80
18	68	2332	158576	150	2.38
19	38	4068	154584	150	2.32
20	62	2550	158100	150	2.37
21	35.5	5500	195250	150	2.93
22	130.5	3600	469800	150	7.05
				Total	93.38

Table 6.14: Cost Estimation for flood mitigation Scenario 2.3

Cross Section	Area (m^2) for 1.5m dredging	Length(m)	Volume (cumec)	Dredging cost (Tk.)	Total cost (Crore Tk.)
2	195	2800	546000	150	8.19
3	143.25	4750	680437.5	150	10.21
4	189	3500	661500	150	9.92
5	282.75	3807	1076429.25	150	16.15
6	274.5	5043	1384303.5	150	20.76
7	210.75	3300	695475	150	10.43
8	312	4584	1430208	150	21.45
	Area (m^2) for 1.0m dredging				
15	58	2500	145000	150	2.18
16	54.5	3200	174400	150	2.62
17	201.5	2250	453375	150	6.80
18	68	2332	158576	150	2.38
19	38	4068	154584	150	2.32
20	62	2550	158100	150	2.37
21	35.5	5500	195250	150	2.93
22	130.5	3600	469800	150	7.05
				Total	125.76

Table 6.15: Cost Estimation for flood mitigation Scenario 3.1

Embankment height(m)	Area (meter square)	Length (km)	Volume (cumec)	Cost per cumec According to BWDB (Tk.)	Cost (Crore Tk.)	Total Cost (Crore Tk.)
0.5	2	37	74000	500	3.7	3.7
Cross Section	**Area(m^2) for 0.5m dredging**	**length(m)**	**volume (cumec)**	**dredging cost**	**Cost**	
15	29	2500	72500	150	1.09	14.16
16	27.25	3200	87200	150	1.31	
17	100.75	2250	226687.5	150	3.40	
18	34	2332	79288	150	1.19	
19	19	4068	77292	150	1.16	
20	31	2550	79050	150	1.19	
21	17.75	5500	97625	150	1.46	
22	62.25	3600	224100	150	3.36	
					Total	17.86

Table 6.16: Cost Estimation for flood mitigation Scenario 3.2

<table>
<tr><th>Embankment height(m)</th><th>Area (meter square)</th><th>Length (km)</th><th>Volume (cumec)</th><th>Cost per cumec According to BWDB (Tk.)</th><th>Cost (Crore Tk.)</th><th>Total Cost (Crore Tk.)</th></tr>
<tr><td>1</td><td>5</td><td>20</td><td rowspan="2">210160</td><td rowspan="2">500</td><td rowspan="2">10.51</td><td rowspan="2">10.51</td></tr>
<tr><td>1.2</td><td>6.48</td><td>17</td></tr>
<tr><th>Cross Section</th><th>Area (m^2) for 1.0m dredging</th><th>Length (m)</th><th>volume (cumec)</th><th>Dredging cost</th><th>Cost</th><th></th></tr>
<tr><td>15</td><td>58</td><td>2500</td><td>145000</td><td>150</td><td>2.18</td><td rowspan="8">28.64</td></tr>
<tr><td>16</td><td>54.5</td><td>3200</td><td>174400</td><td>150</td><td>2.62</td></tr>
<tr><td>17</td><td>201.5</td><td>2250</td><td>453375</td><td>150</td><td>6.80</td></tr>
<tr><td>18</td><td>68</td><td>2332</td><td>158576</td><td>150</td><td>2.38</td></tr>
<tr><td>19</td><td>38</td><td>4068</td><td>154584</td><td>150</td><td>2.32</td></tr>
<tr><td>20</td><td>62</td><td>2550</td><td>158100</td><td>150</td><td>2.37</td></tr>
<tr><td>21</td><td>35.5</td><td>5500</td><td>195250</td><td>150</td><td>2.93</td></tr>
<tr><td>22</td><td>130.5</td><td>3600</td><td>469800</td><td>150</td><td>7.05</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>Total</td><td>39.14</td></tr>
</table>

The summary of total cost for flood mitigation scenario 1.1 to scenario 3.2 has been given in table 6.17.

Table 6.17: Summary of total Cost for flood mitigation Scenario 1.1 to 3.2

Scenarios	Flood Inundated Area (sq.km)	Flood Inundated Area (%)	Total Cost (Crore Tk.)
Scenario 1.1	237.34	15.49	7.4
Scenario 1.2	164.74	10.75	11.40
Scenario 1.3	133.58	8.72	22.50
Scenario 1.4	52.14	3.40	36.24
Scenario 2.1	222.21	14.50	46.02
Scenario 2.2	121.43	7.93	93.38
Scenario 2.3	106.47	6.95	125.76
Scenario 3.1	194.47	12.69	17.86
Scenario 3.2	35.30	2.30	39.14

6.6 Discussion

This study focuses on the flood inundated area of Ghaghat River and find out the best possible way of mitigate flood of this area. For this purpose, a hydro-dynamic model of Ghaghat River has established the inundated area of this region. The model performance suggested that the

1D hydro-dynamic model calibration and validation was satisfactory. After calibration and validation of the 1D-2D coupled model, it has been simulated for the historical flood events of 2004, 2007, 2011, 2012 and 2017 in which inundated area were 295.34 km^2, 25.90 km^2, 89.17 km^2, 107.70 km^2 and 136.64 km^2 respectively. According to the inundation map from the model it has found that maximum 19.27% area of Ghaghat river floodplain has inundated in the year of 2004. As maximum inundation area has been found in 2004 that's why flood mitigation scenarios are compared with the results from simulated model of 2004.

In this Study, three scenarios have been established for mitigation of flood of this area. Extension of existing embankment, raising height of embankment and construction of new embankment in scenarios 1.1 to scenarios 1.4 has been implemented. Among these four-scenario maximum percentage of flood mitigation has found for scenario 3.2. According to simulated results maximum percentage of flood mitigation has found 3.4% in scenario 1.4 in which existing embankment has raised to a height up to 1.25m and new embankment of height of 0.5 to 1m up to 77 kilometers on both side of the river. The percentage of flood inundated area from flood mitigation has been found 6.95% for scenario 2.3 where dredged section has provided from cross-section 2 to 9 and cross-section 15 to 22. For scenario 3.2, maximum percentage of flood mitigation has been found 2.30% for raising the existing embankment height by 1 meter up to 20 kilometers at both left & right bank and 1.2 meter from 20 kilometers to 37 kilometers from downstream at left bank and from 20 kilometers to 27.5 kilometers at right bank and construction of new embankment of 1.2m height from existing right bank from 27.5 kilometers to 37 kilometers at right bank and dredging 1.0 meter from cross-sections 15 to 22 (49.5-73) kilometers.

Moreover, cost estimation has been introduced in this study then it can be noticed that 36.24 crore Tk. has been estimated for implementation of embankment for flood mitigation scenario 1.4. All the cost including construction work, labor cost, material cost etc. Total 125.76 crore Tk. has been estimated for implementation of dredging for flood mitigation scenario 2.3. On the other hand, maximum reduction of flood inundation area has been found for flood mitigation scenario 3.2 which costs 39.14 crore Tk. On the basis of cost estimation and reduced percentage of flood mitigation, scenario 3.2 has been suggested for maximum percentage of flood mitigation.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 General

In this study, flood inundation mapping of Ghaghat River has been assessed by using HEC-RAS hydrodynamic model on the basis of different mitigation scenarios. For development of inundation model in Ghaghat River floodplain, 1D/2D couple model has been used in this study. Geographical Information System has been used for further development of the flood inundation map based on results of mitigation scenarios from the model.

7.2 Conclusions of the Study

1. Calibration and validation of 1D hydrodynamic model have been performed in 2013 and 2015 respectively where Manning's roughness co-efficient 'n' is the key parameter for calibration and validation. For calibration and validation, the water level data of the station (Mirjapur) has been used. The result showed a good correlation between the observed and simulated water level data for Manning's roughness coefficient n = 0.020 from downstream to cross-section station 18 and n = 0.021 for rest of the rivers of the system.
2. The value of correlation coefficient, R^2 is 0.9596 and 0.9027 for calibration and validation respectively and the value of NSE is 0.956 and 0.730 for calibration and validation respectively which were found in acceptable range. These co-efficient has shown a satisfactory correlation between simulated and observed water level.
3. After calibration and validation, FFWC observed map on 23rd August, 2004 has been used for flood inundation comparison. Comparison among FFWC observed map, satellite image and simulated map result has found satisfactory which leads this model for further flood analysis. Later, 1D-2D coupled model of Ghaghat River is simulated for the historical flood events of 2004, 2007, 2011, 2012 and 2017 in which 295.34 km^2, 157.79 km^2, 89.17 km^2, 107.70 km^2 and 136.64 km^2 of the were inundated which covered 19.28%, 10.30%, 5.82%, 7.03%, and 8.92% of the total study area's flood water respectively. The maximum inundation area has found for 2004.
4. The total inundated area has found 237.34 km^2, 164.74 km^2, 133.58 km^2, 52.14 km^2, 222.21 km^2, 121.43 km^2, 106.47 km^2, 194.47 km^2 and 35.30 km^2 in 2004 which covered about 15.49%, 10.75%, 8.72%, 3.40%, 14.50%, 7.93%, 6.95%, 12.69% and 2.30% of study area from flood mitigation scenario 1.1, Scenario 1.2, Scenario 1.3,

Scenario 1.4, Scenario 2.1, Scenario 2.2, Scenario 2.3, Scenario 3.1 and Scenario 3.2 respectively.

5. From all the flood mitigation scenarios, minimum flood inundation area has found about 2.30% of the study area for 2004 for scenarios-3.2. Among all of them scenario-3.2 has been suggested not only for reduction of maximum percentage of area inundated but also low-cost estimation compared to other scenarios.

7.3 Recommendations for Future Studies

The following measures can be recommended for the improvement of this study in future.

- Digital elevation model is an essential part to enhance the capability of model. It is recommended to use high-resolution digital spatial database for real replication of topography for the better performance of the model.
- In the present research three options were taken into consideration for selecting flood mitigation scenarios. In order to reduce flood depth at a considerable range in flood inundation area for future study, it is recommended to select some additional scenarios (flow regulating structure, channelization etc.) in order to mitigate flood.
- Generation of flood hazard map and flood risk map using hazard parameters such as flooding duration, velocity, and shear stress can be performed for future study.

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APPENDIX A

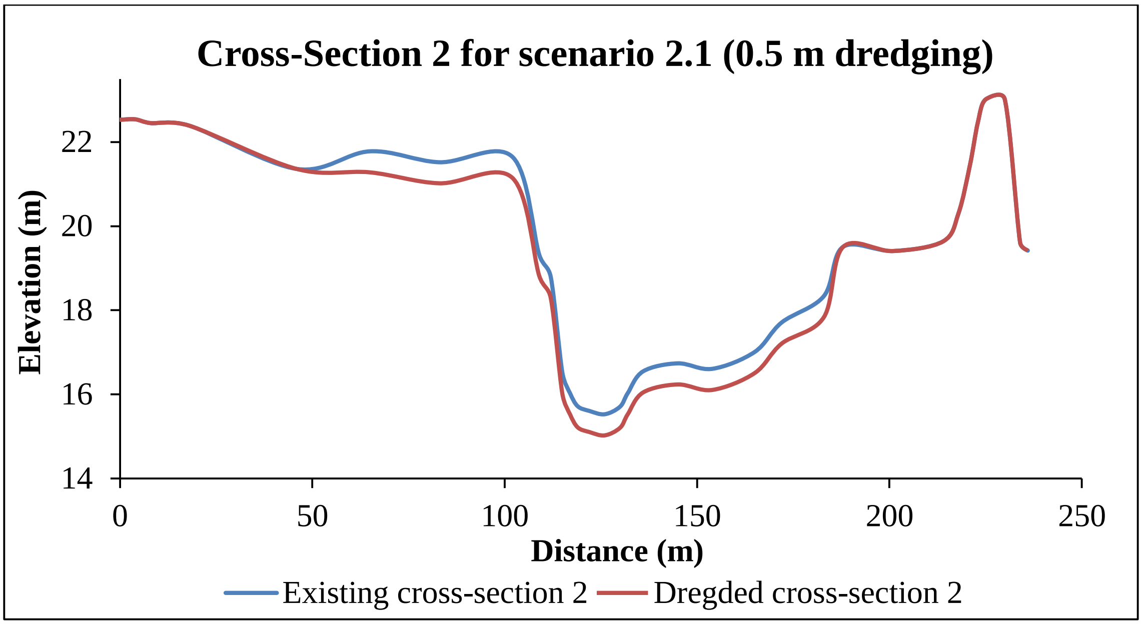

Figure A1: Cross-Section 2 for scenario 2.1 (0.5 m dredging)

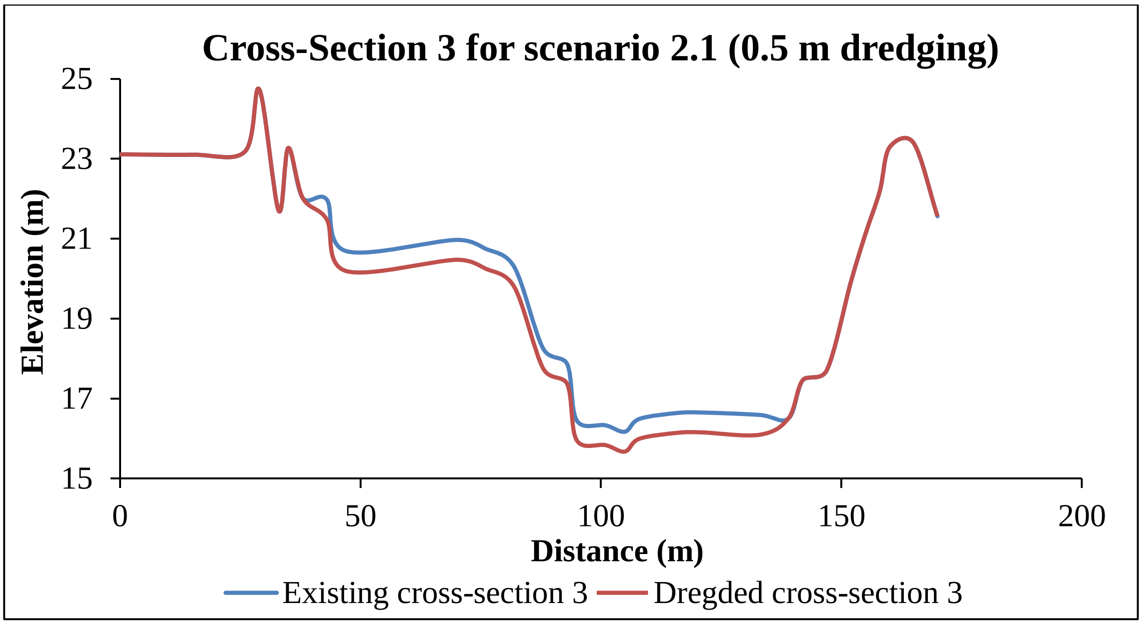

Figure A2: Cross-Section 3 for scenario 2.1 (0.5 m dredging)

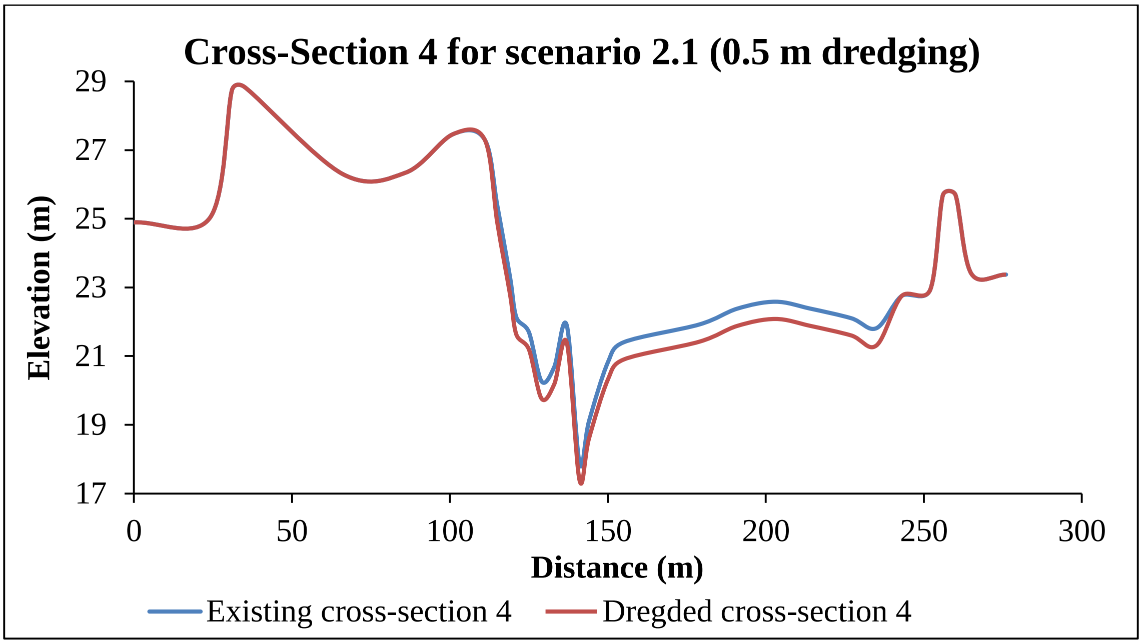

Figure A3: Cross-Section 4 for scenario 2.1 (0.5 m dredging)

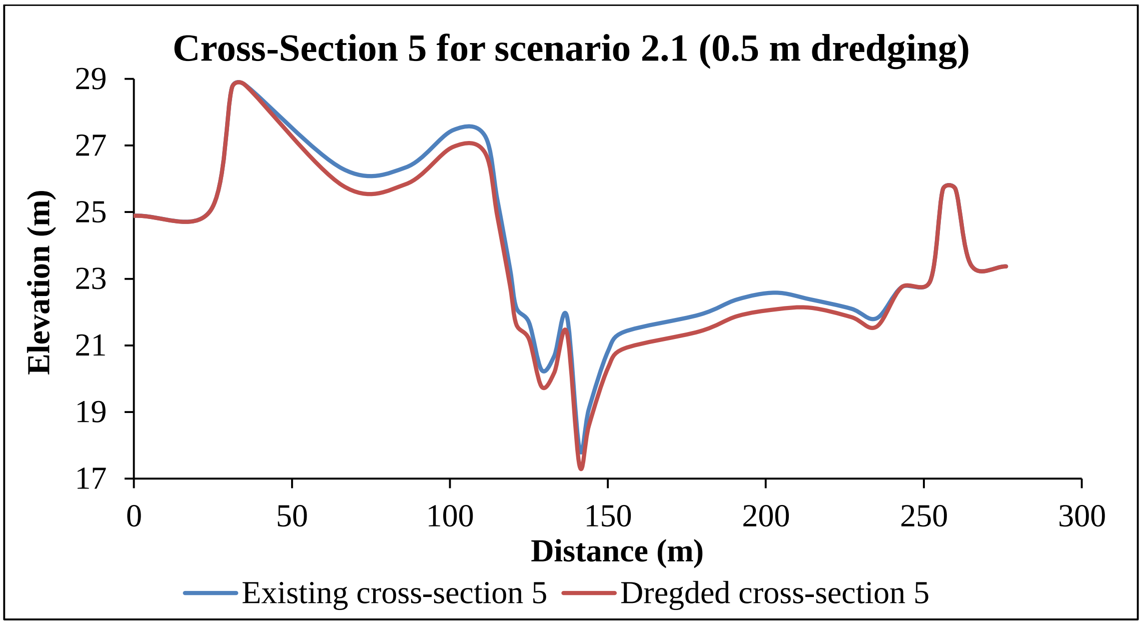

Figure A4: Cross-Section 5 for scenario 2.1 (0.5 m dredging)

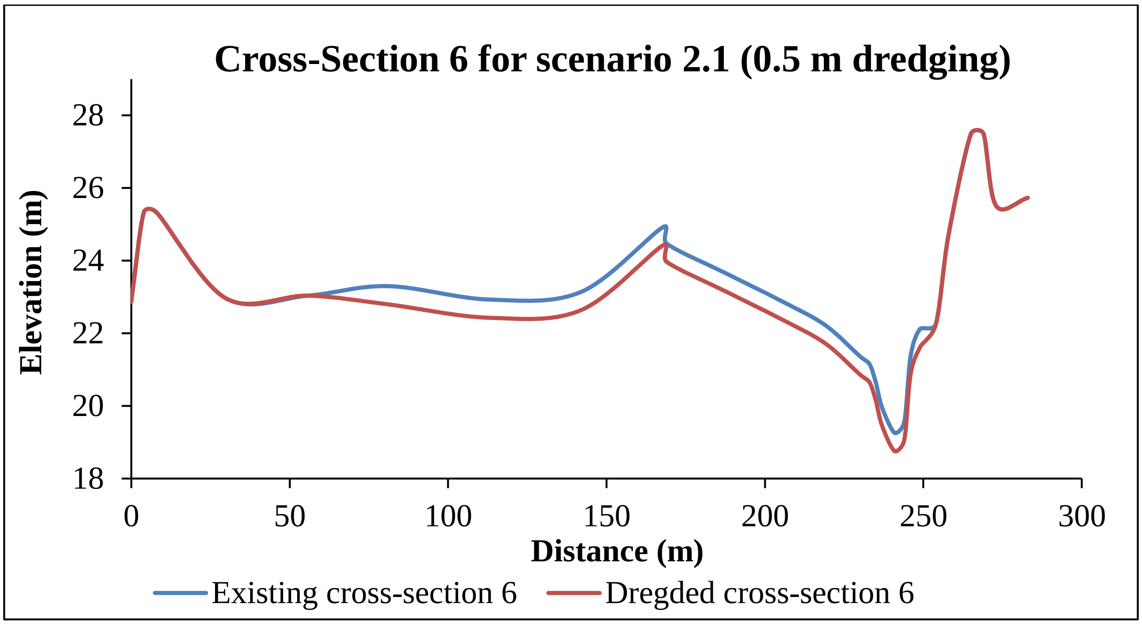

Figure A5: Cross-Section 6 for scenario 2.1 (0.5 m dredging)

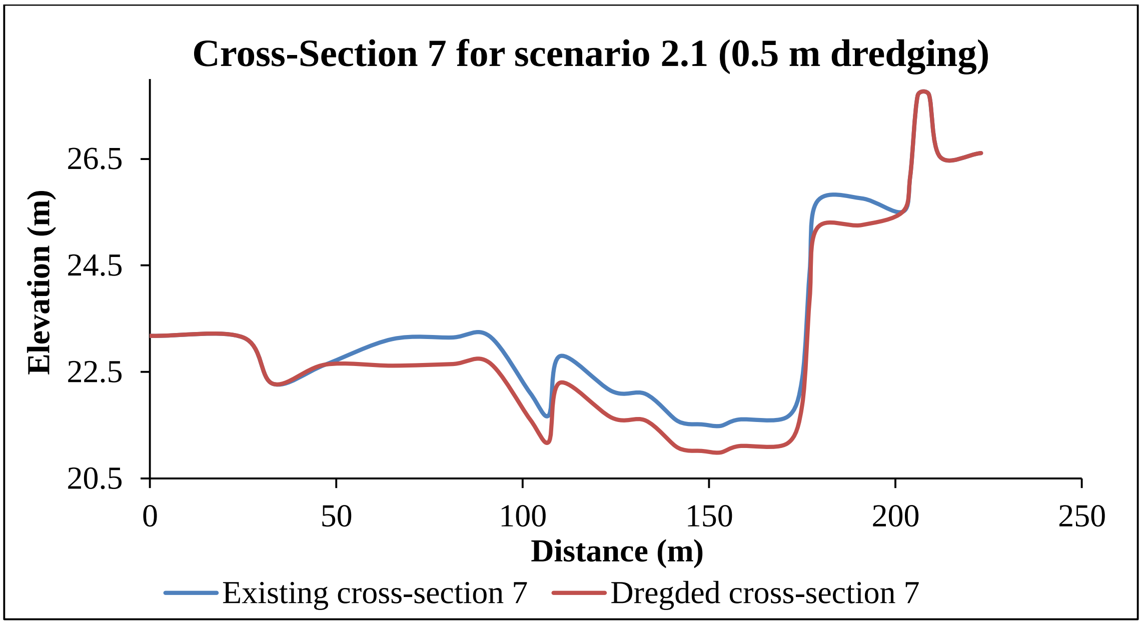

Figure A6: Cross-Section 7 for scenario 2.1 (0.5 m dredging)

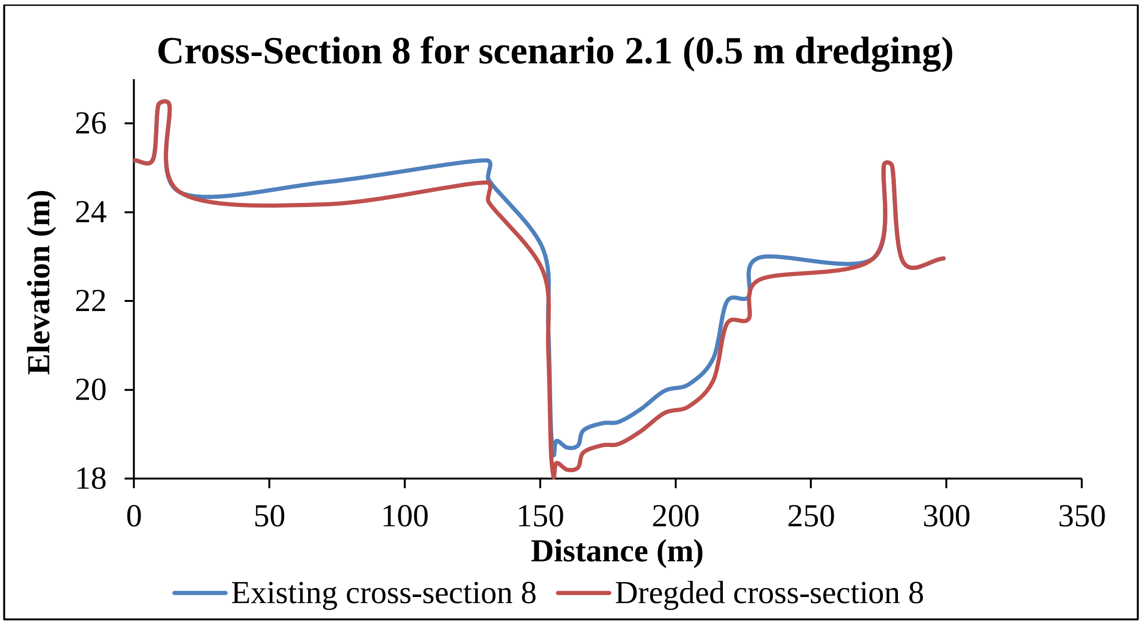

Figure A7: Cross-Section 8 for scenario 2.1 (0.5 m dredging)

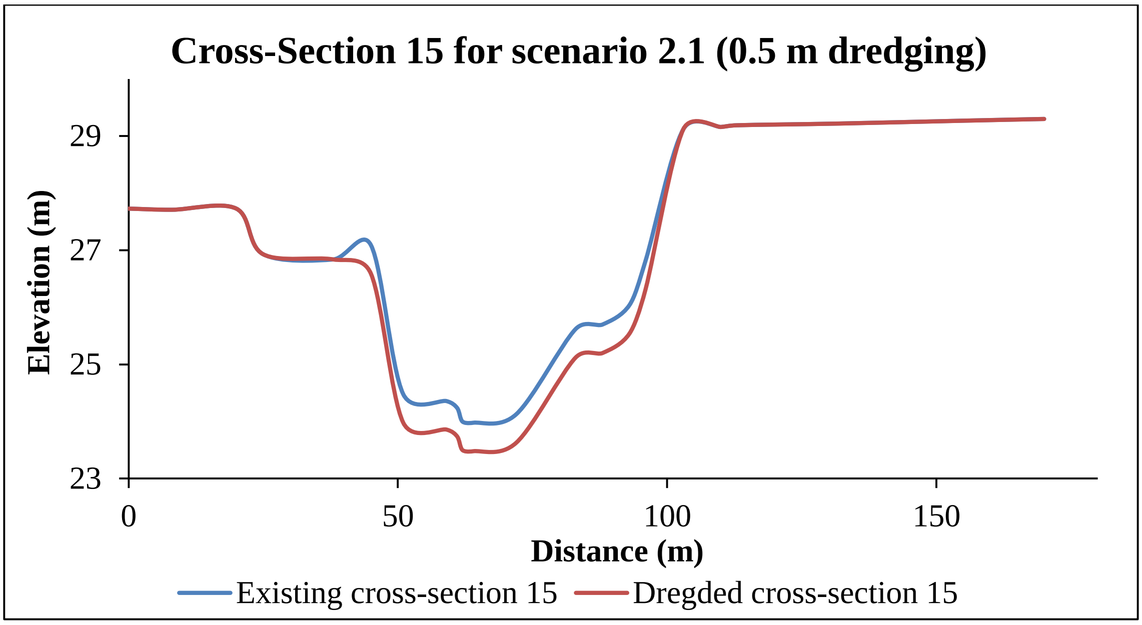

Figure A8: Cross-Section 15 for scenario 2.1 (0.5 m dredging)

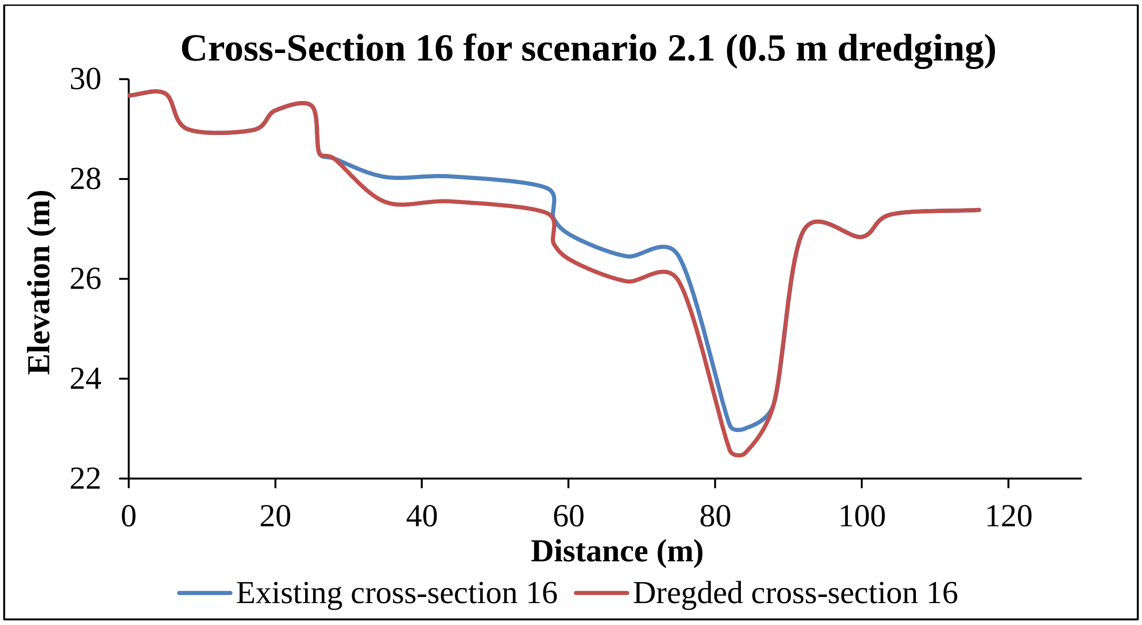

Figure A9: Cross-Section 16 for scenario 2.1 (0.5 m dredging)

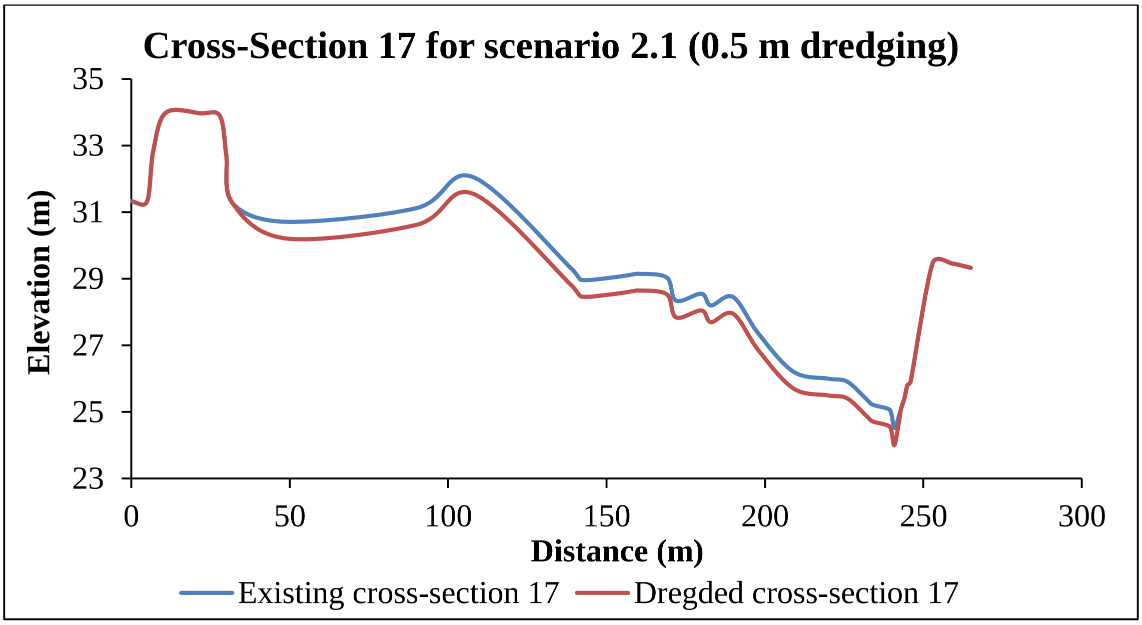

Figure A10: Cross-Section 17 for scenario 2.1 (0.5 m dredging)

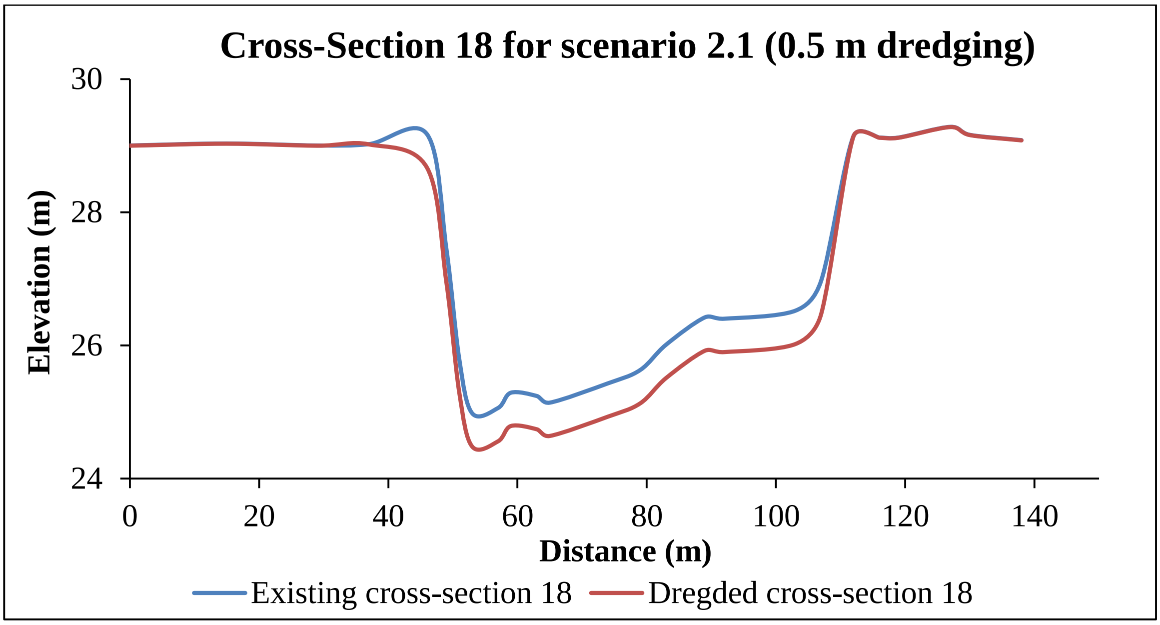

Figure A11: Cross-Section 8 for scenario 2.1 (0.5 m dredging)

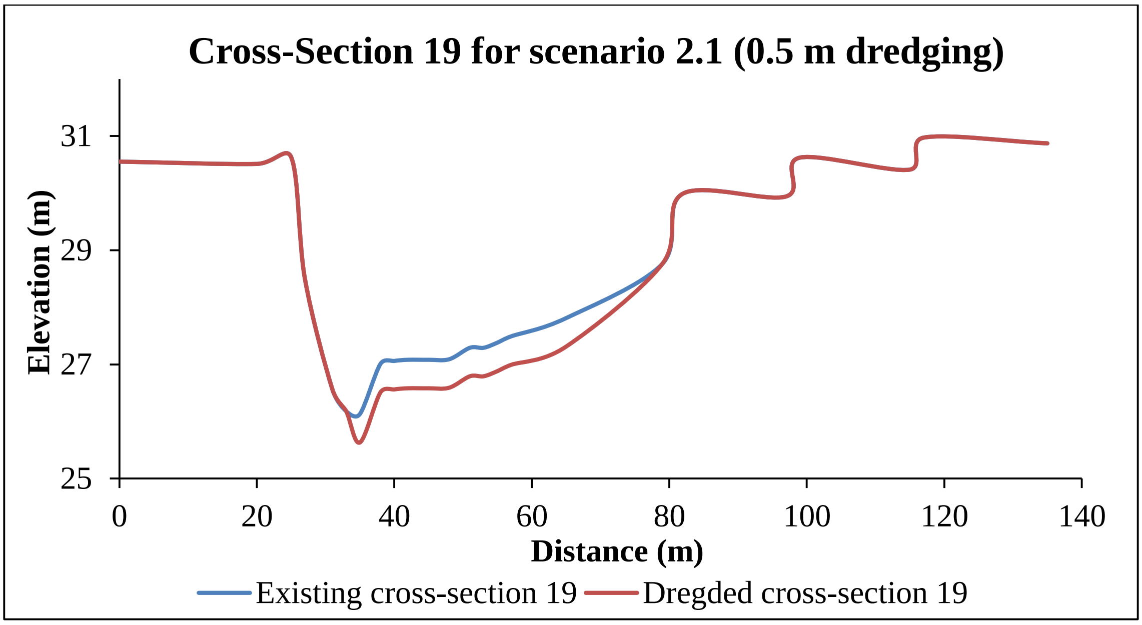

Figure A12: Cross-Section 19 for scenario 2.1 (0.5 m dredging)

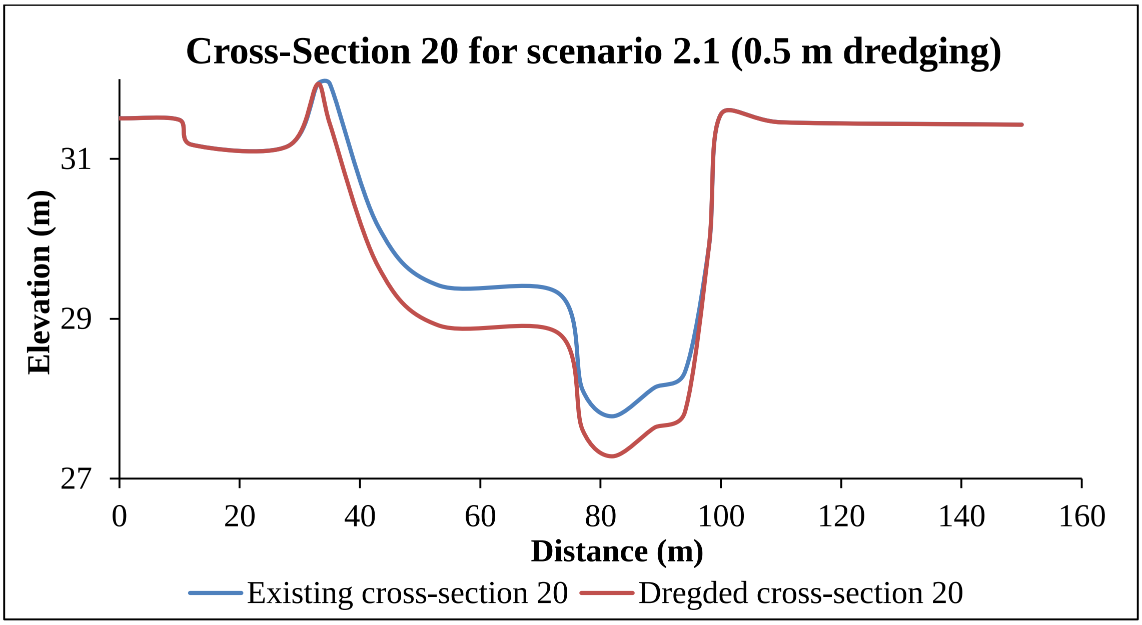

Figure A13: Cross-Section 20 for scenario 2.1 (0.5 m dredging)

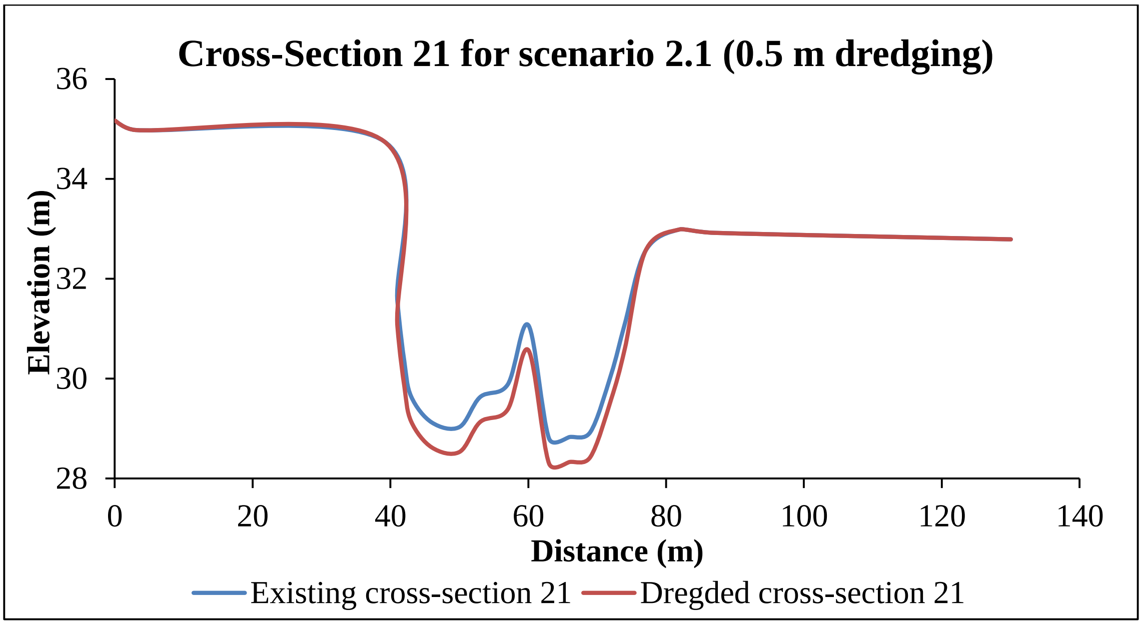

Figure A14: Cross-Section 21 for scenario 2.1 (0.5 m dredging)

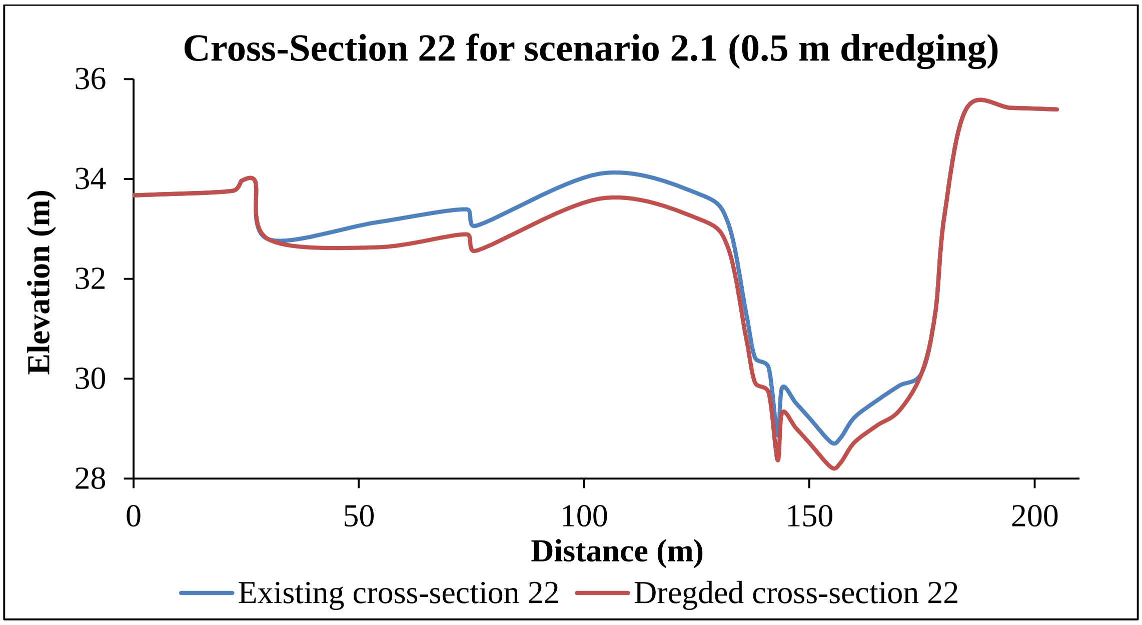

Figure A15: Cross-Section 22 for scenario 2.1 (0.5 m dredging)

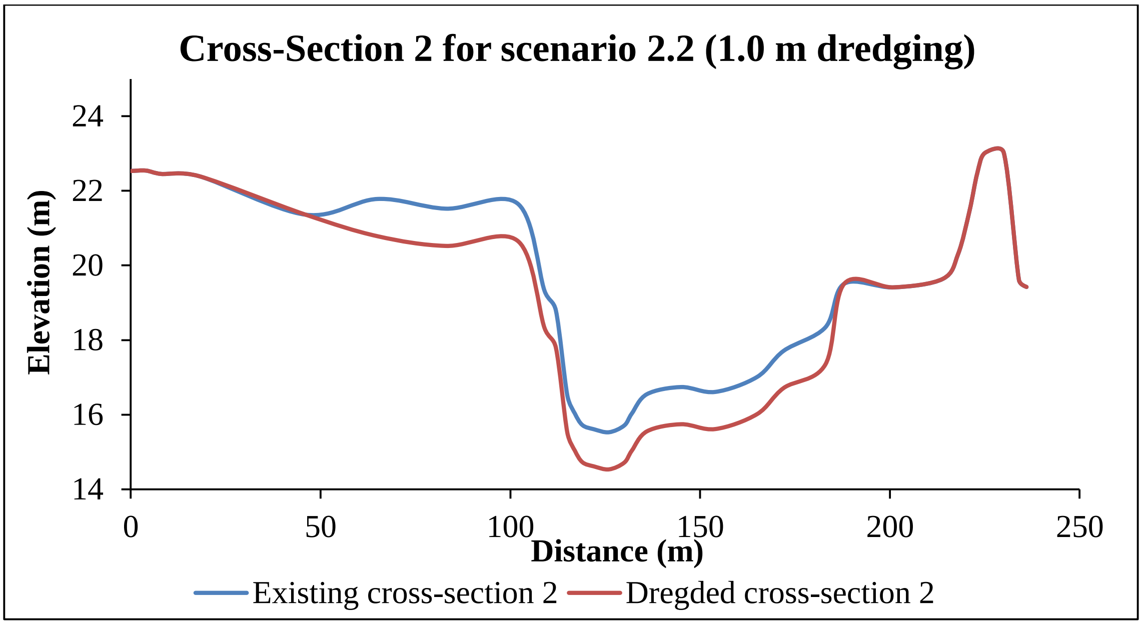

Figure A16: Cross-Section 2 for scenario 2.2 (1.0 m dredging)

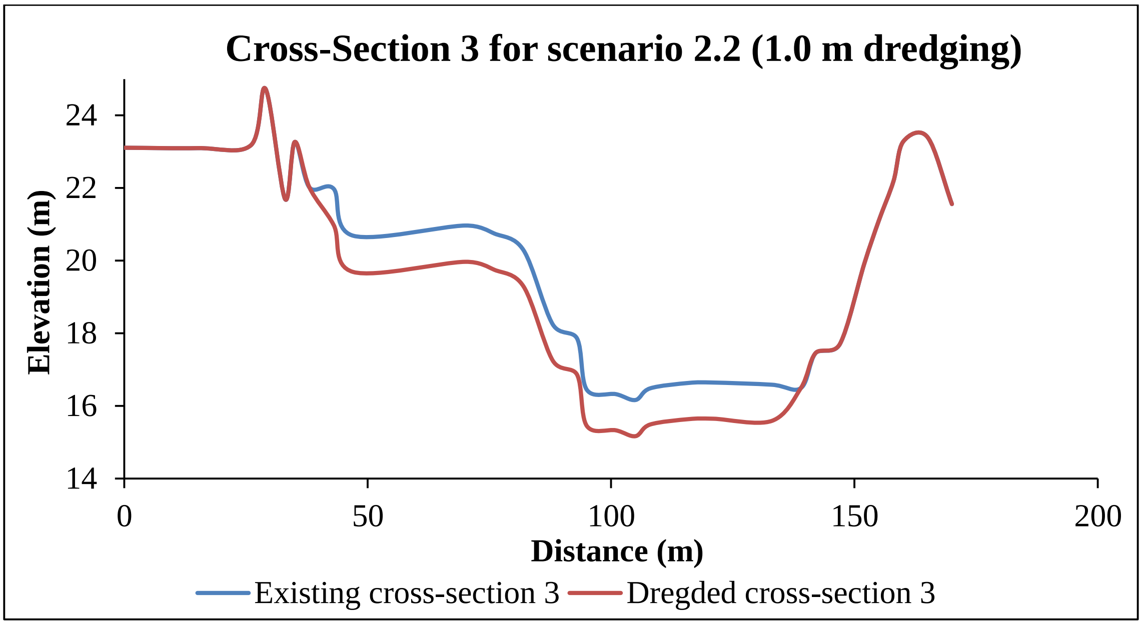

Figure A17: Cross-Section 3 for scenario 2.2 (1.0 m dredging)

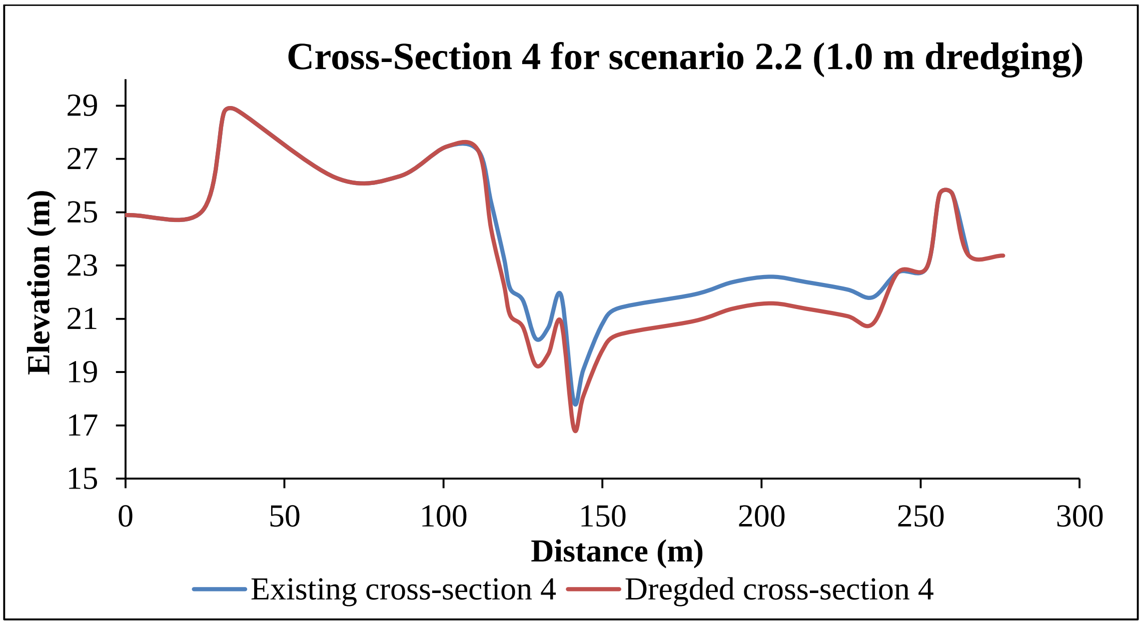

Figure A16: Cross-Section 4 for scenario 2.2 (1.0 m dredging)

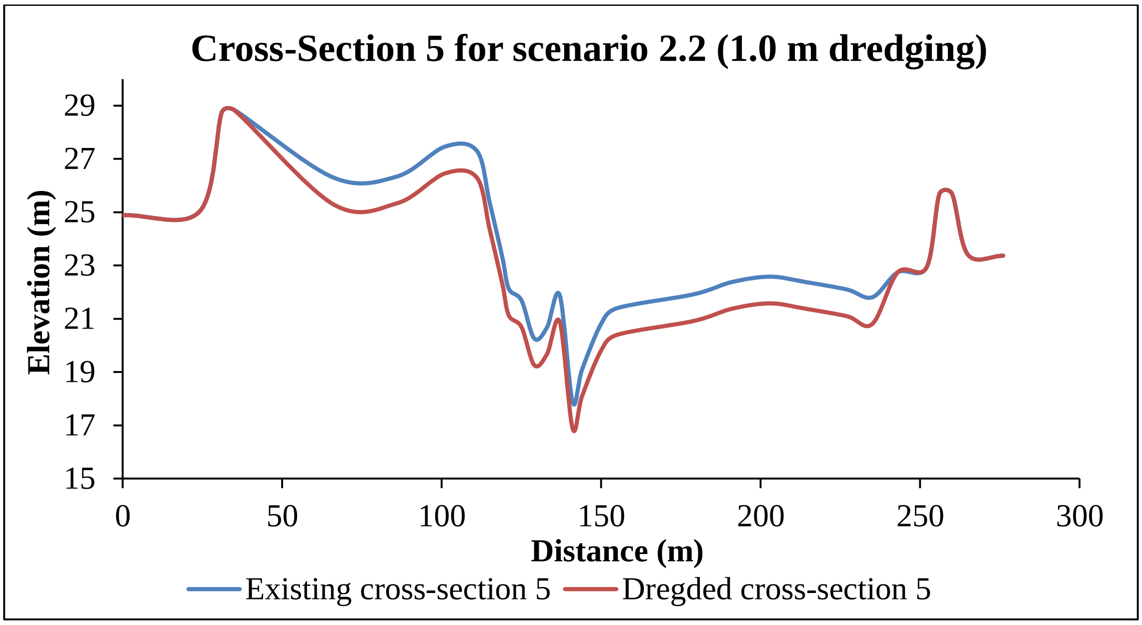

Figure A17: Cross-Section 5 for scenario 2.2 (1.0 m dredging)

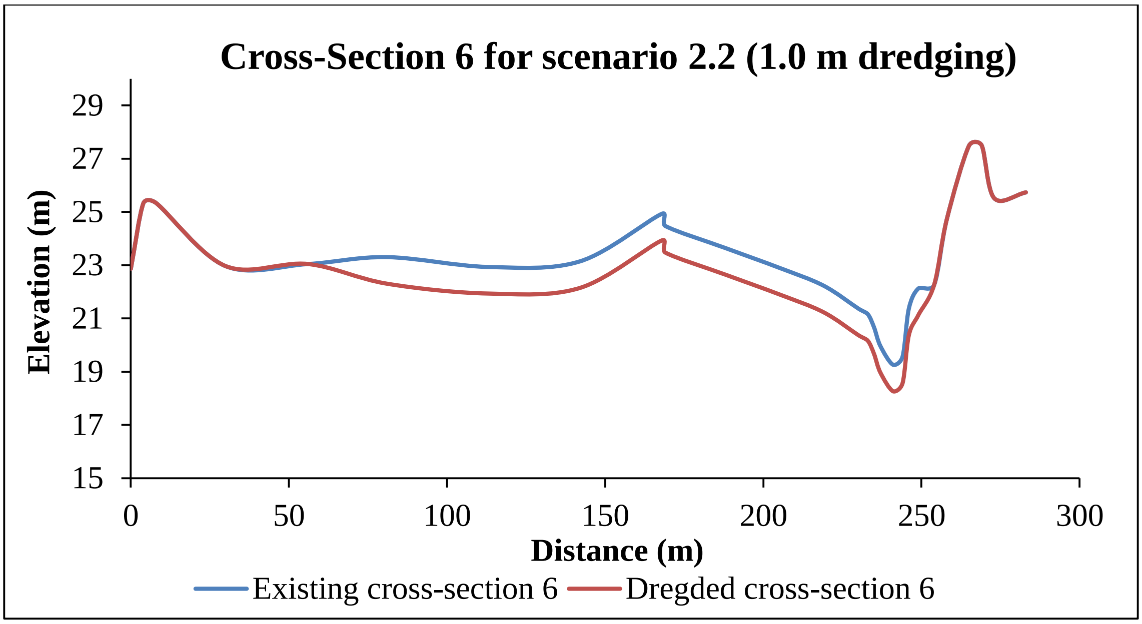

Figure A18: Cross-Section 6 for scenario 2.2 (1.0 m dredging)

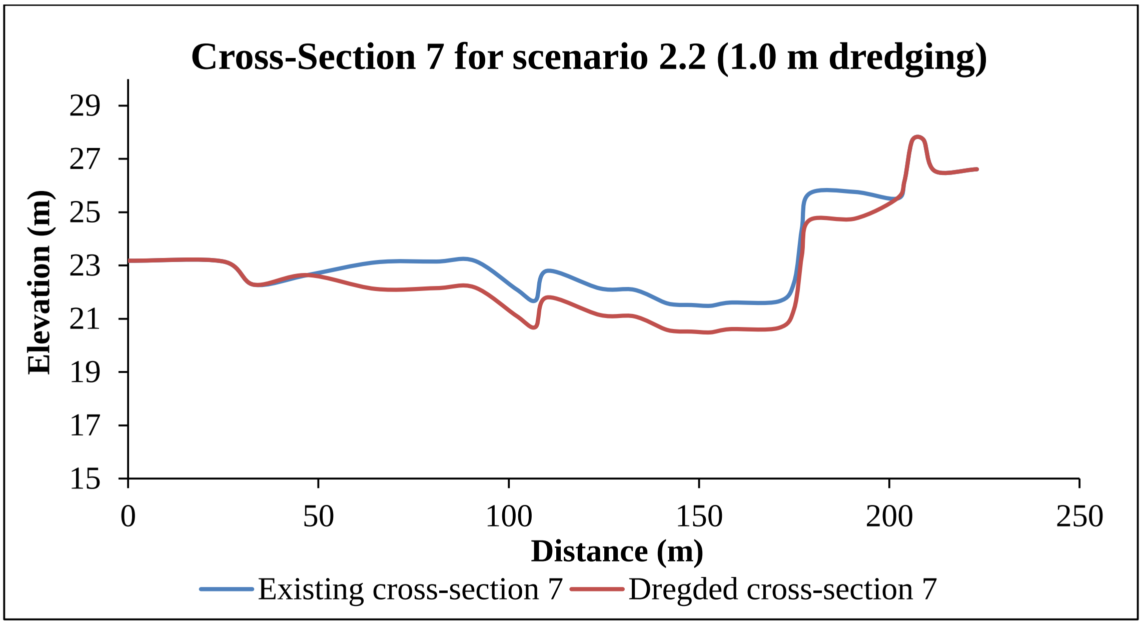

Figure A19: Cross-Section 7 for scenario 2.2 (1.0 m dredging)

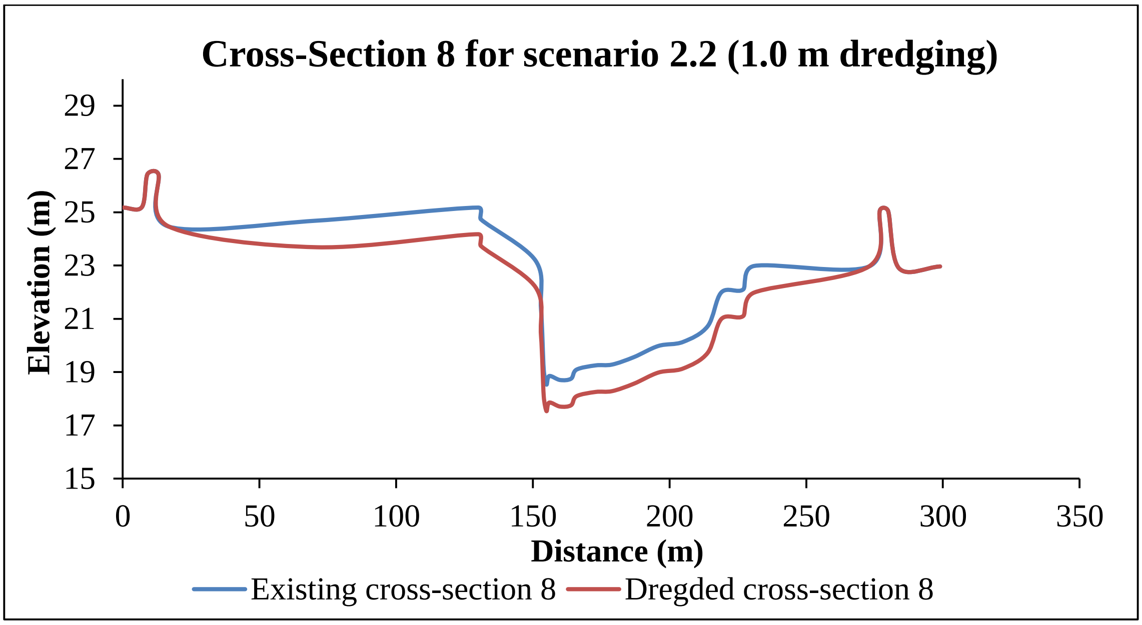

Figure A20: Cross-Section 8 for scenario 2.2 (1.0 m dredging)

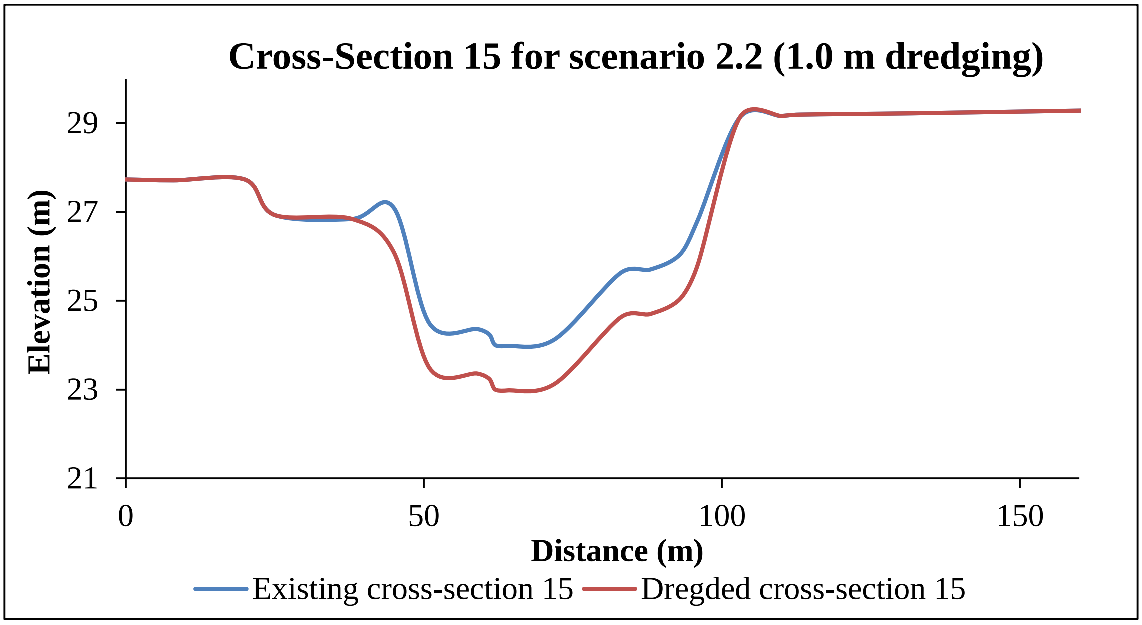

Figure A21: Cross-Section 15 for scenario 2.2 (1.0 m dredging)

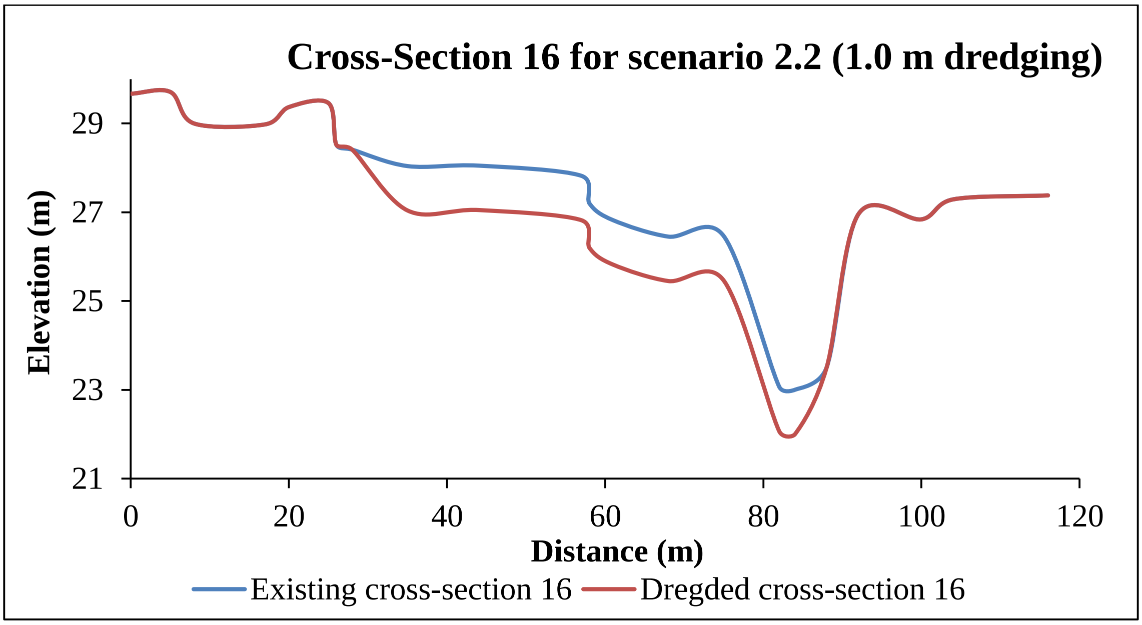

Figure A22: Cross-Section 16 for scenario 2.2 (1.0 m dredging)

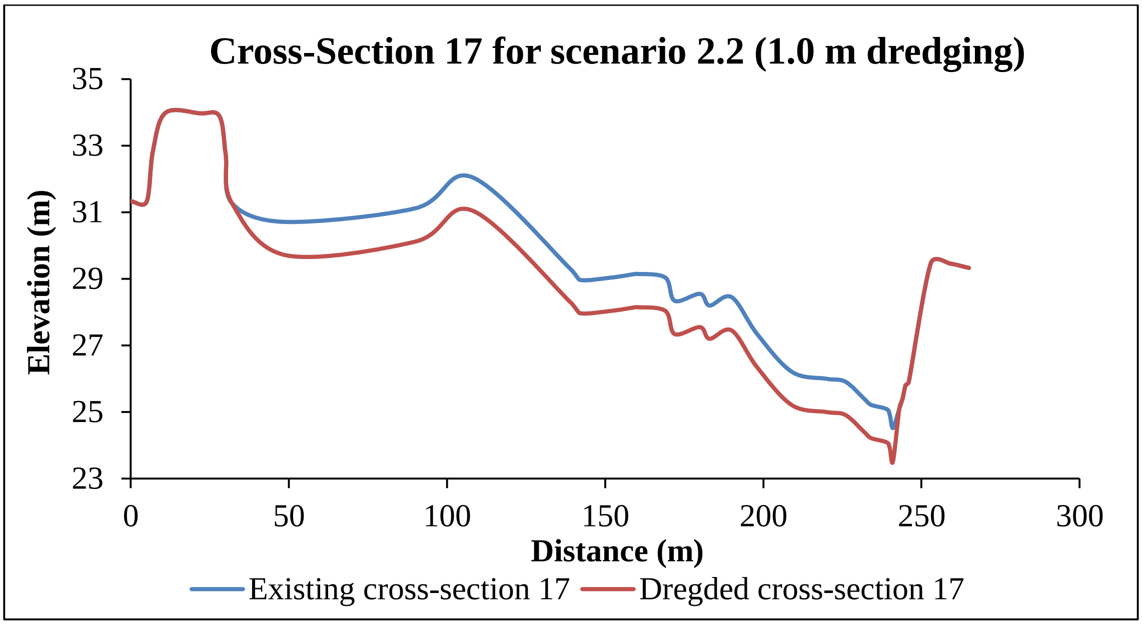

Figure A23: Cross-Section 17 for scenario 2.2 (1.0 m dredging)

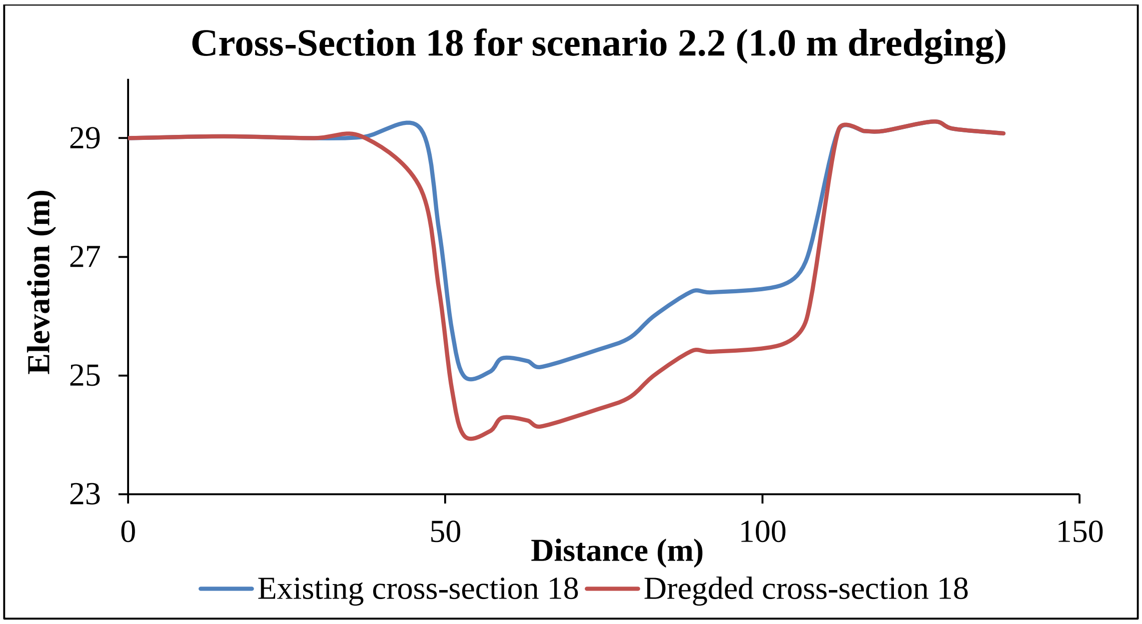

Figure A24: Cross-Section 18 for scenario 2.2 (1.0 m dredging)

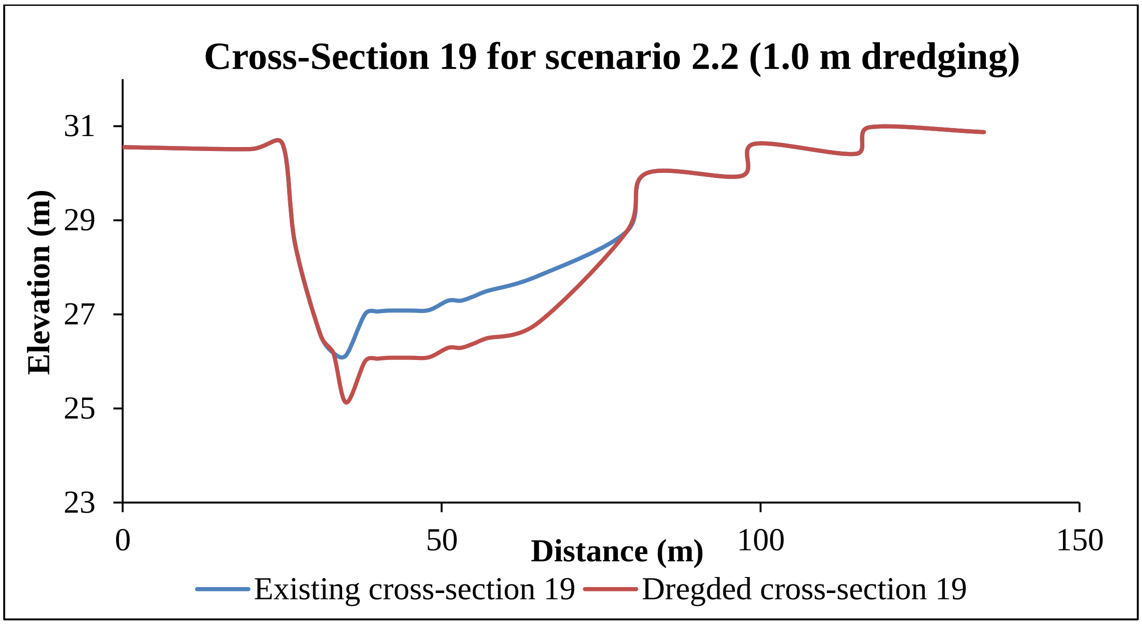

Figure A25: Cross-Section 19 for scenario 2.2 (1.0 m dredging)

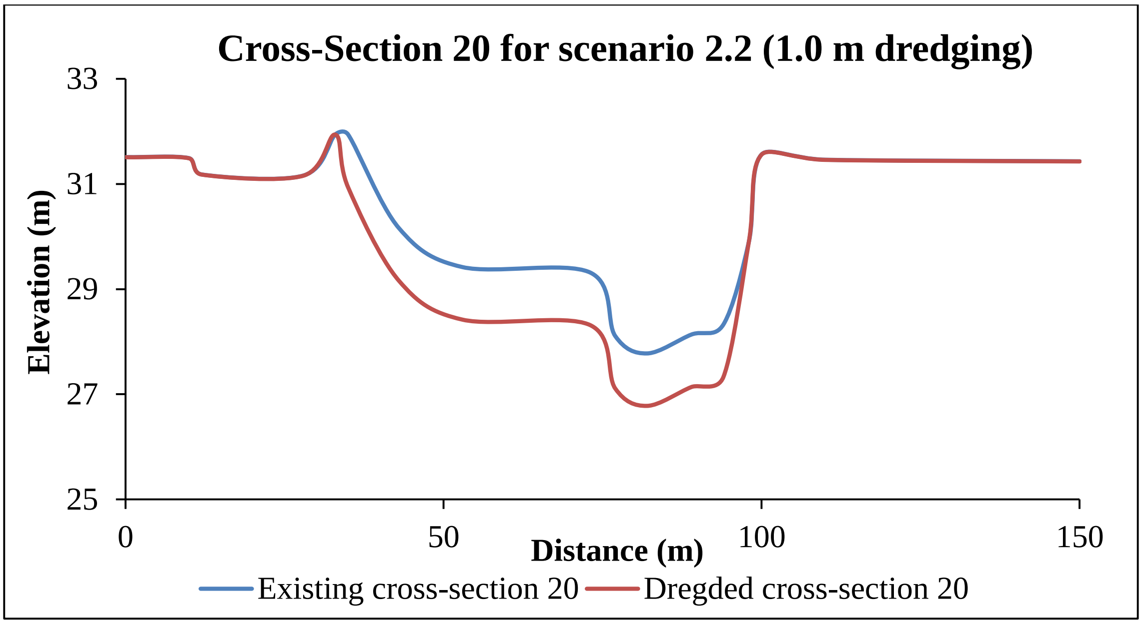

Figure A26: Cross-Section 20 for scenario 2.2 (1.0 m dredging)

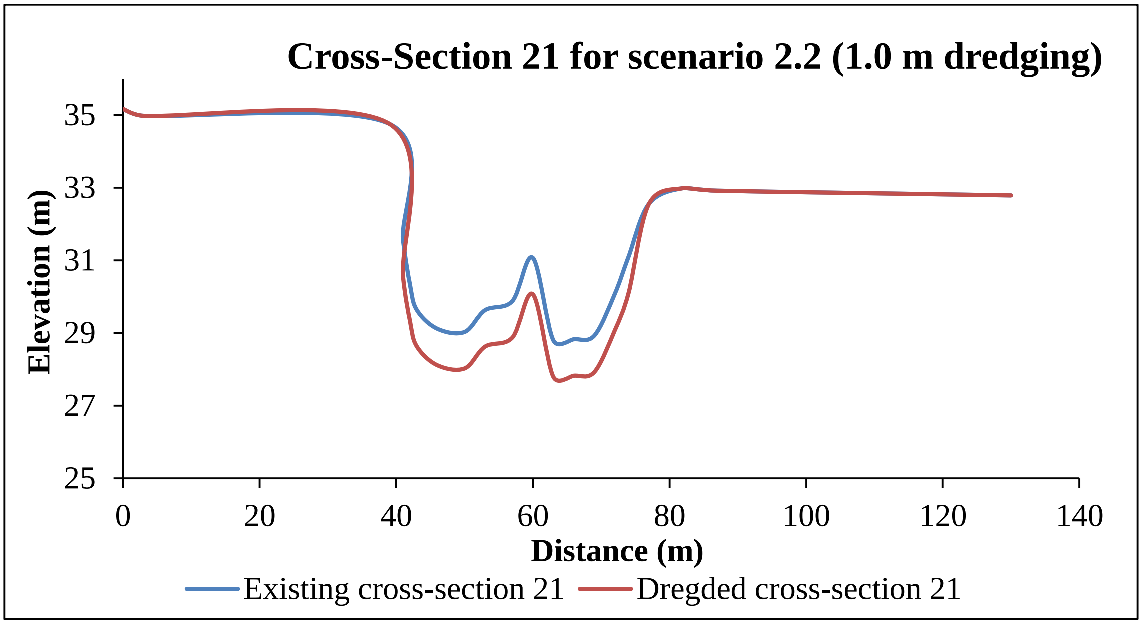

Figure A27: Cross-Section 21 for scenario 2.2 (1.0 m dredging)

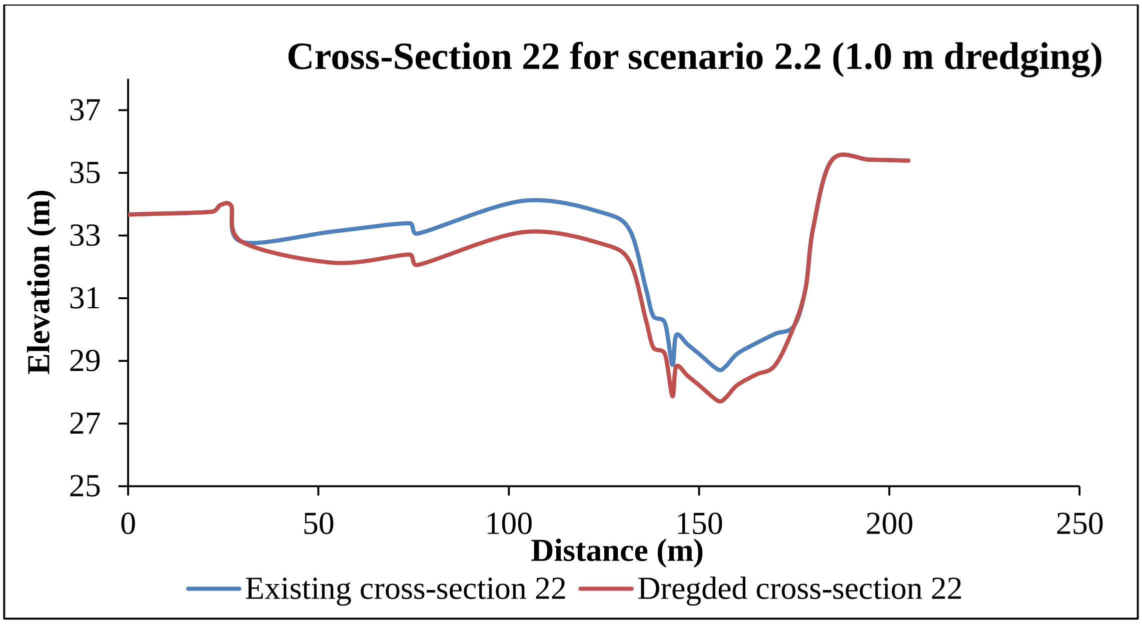

Figure A28: Cross-Section 22 for scenario 2.2 (1.0 m dredging)

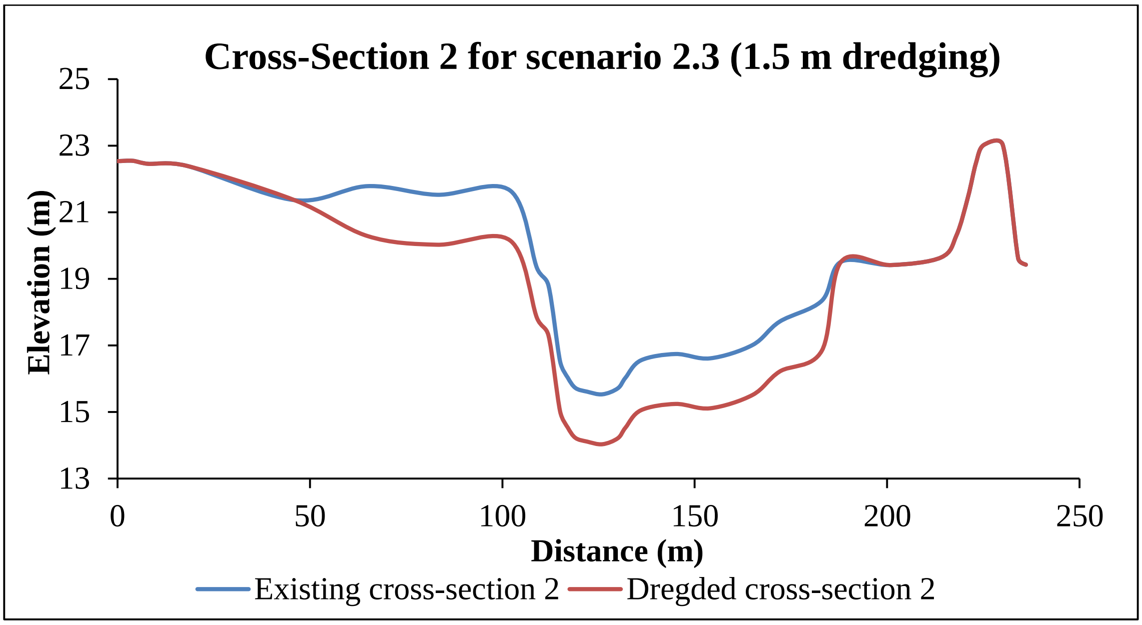

Figure A29: Cross-Section 2 for scenario 2.3 (15 m dredging)

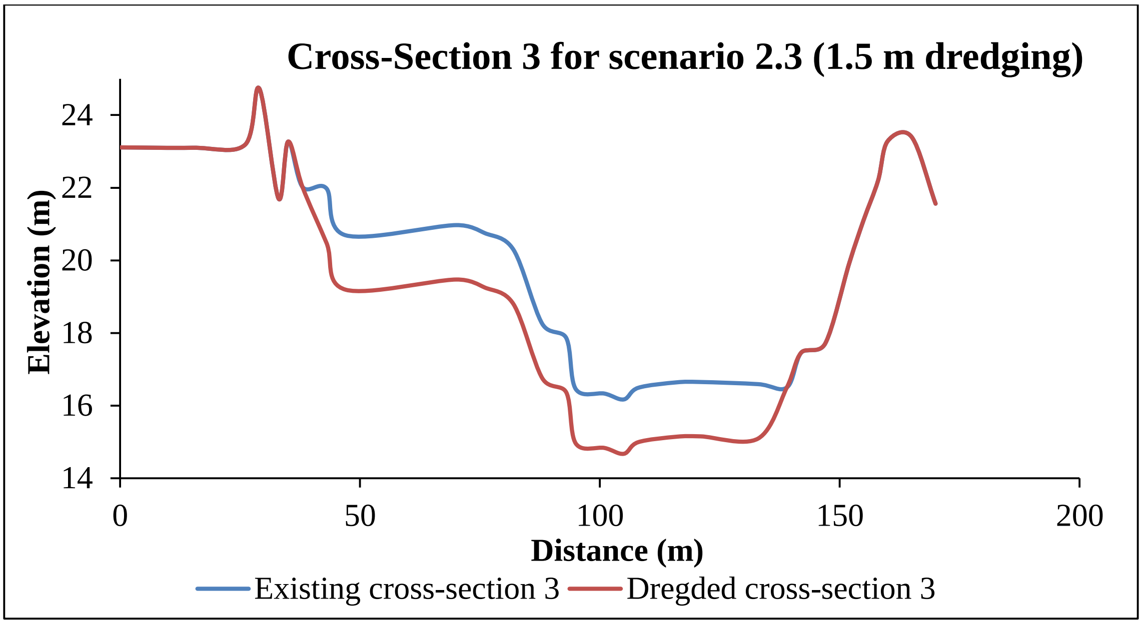

Figure A30: Cross-Section 3 for scenario 2.3 (1.5 m dredging)

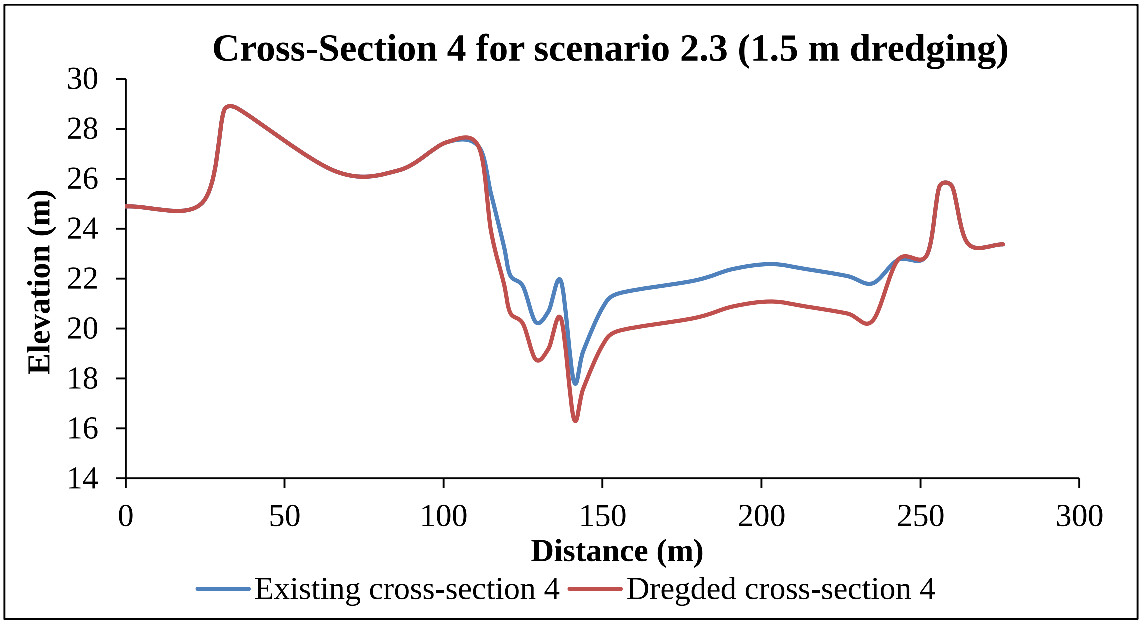

Figure A31: Cross-Section 4 for scenario 2.3 (1.5 m dredging)

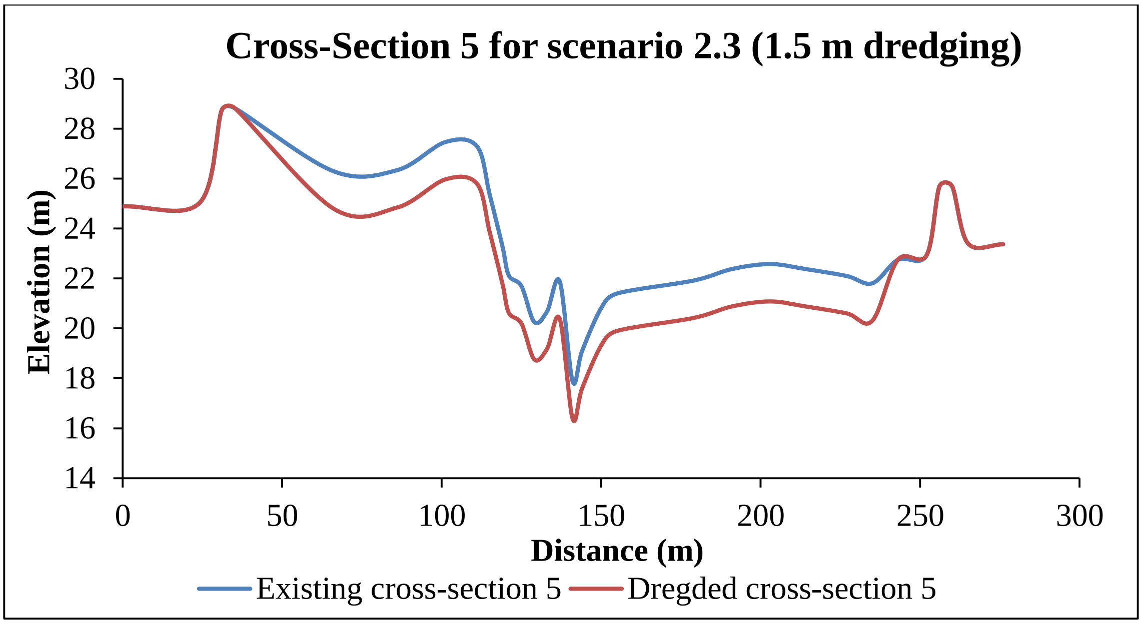

Figure A32: Cross-Section 5 for scenario 2.3 (1.5 m dredging)

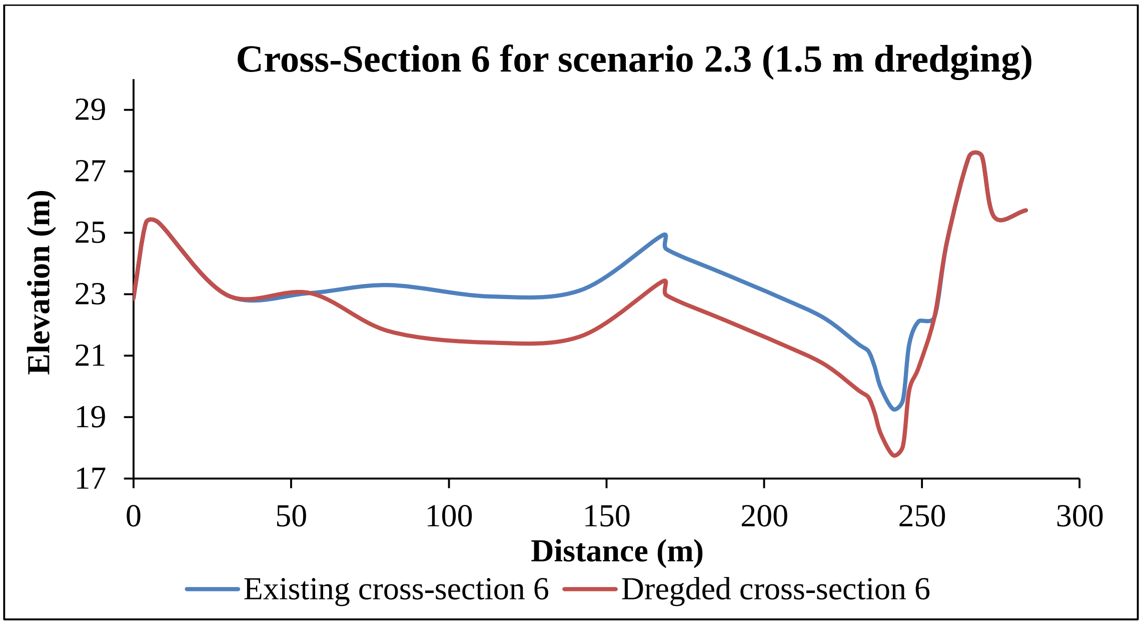

Figure A33: Cross-Section 6 for scenario 2.3 (1.5 m dredging)

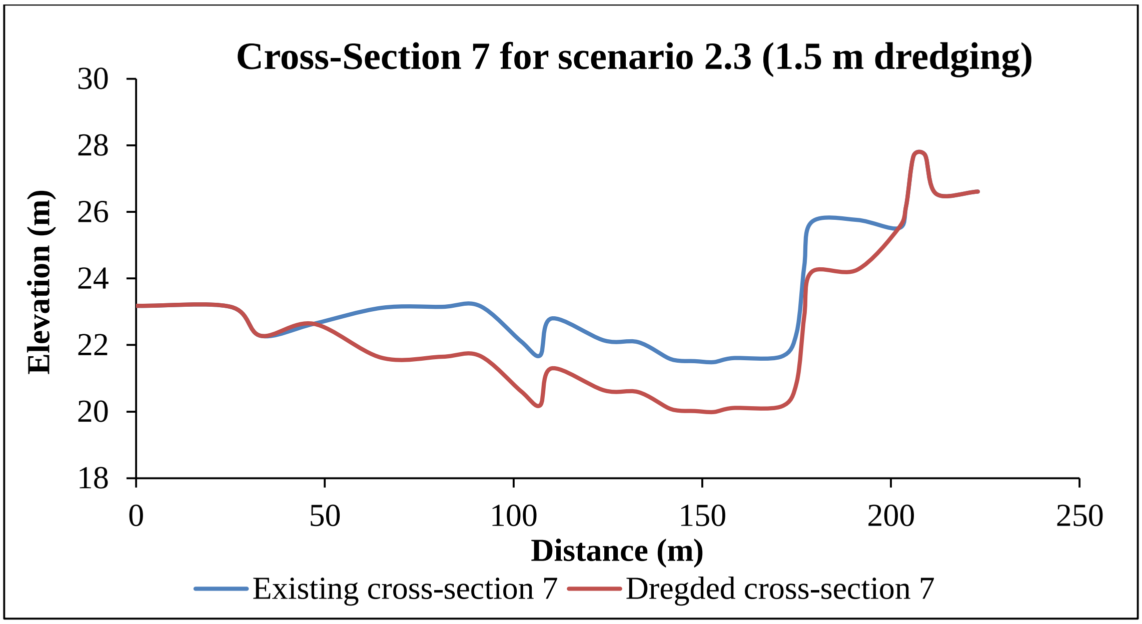

Figure A34: Cross-Section 7 for scenario 2.3 (1.5 m dredging)

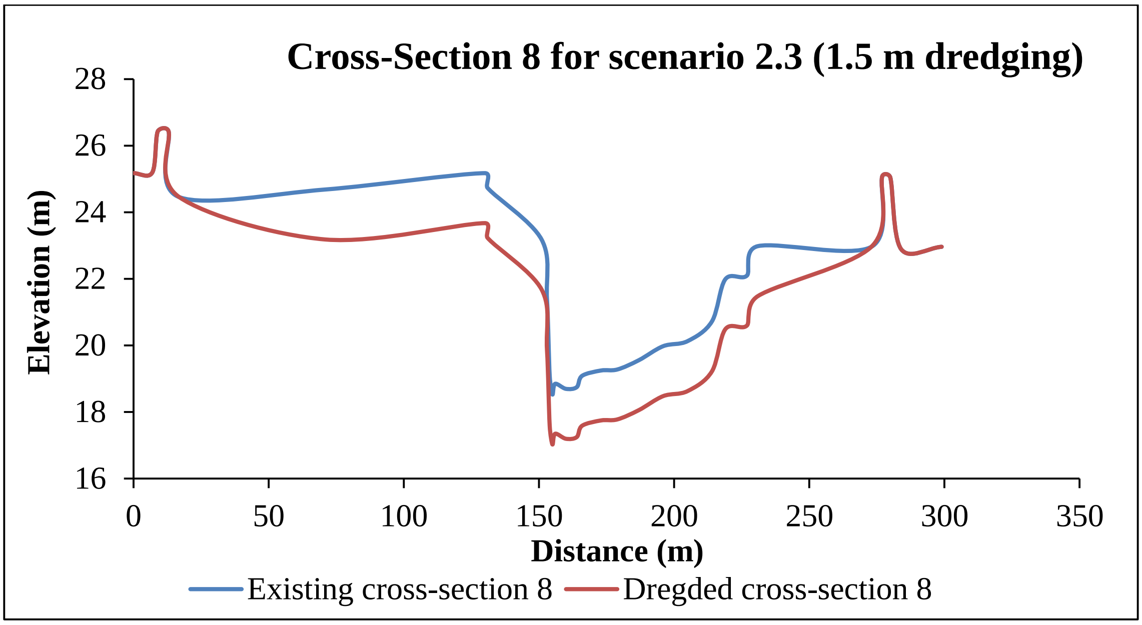

Figure A35: Cross-Section 8 for scenario 2.3 (1.5 m dredging)