MODELING FLOOD INUNDATION OF THE JAMUNA RIVER

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A thesis submitted to the Department of Water Resources Engineering of Bangladesh University of Engineering and Technology, Dhaka, in partial fulfilment of the requirements for the

degree of

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DEPARTMENT OF WATER RESOURCES ENGINEERING

The thesis titled "**Modeling Flood Inundation of the Jamuna River**" submitted by Md. Mostafizur Rahman, Student No: 0412162069 (P), Session: April 2012 has been accepted as satisfactory in partial fulfilment of the requirement for the degree of MASTER OF SCIENCE IN WATER RESOURCES ENGINEERING on 21^{st} March, 2015.

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DECLARATION

I do hereby declare that this Thesis work entitled **"Modeling Flood Inundation of the Jamuna River"** has been done by me under the supervision of Dr. Mohammad Mostafa Ali, Associate Professor, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka. I do hereby declare that any part of it has not been accepted elsewhere for the award of any degree or diploma from any other institution.

21st March 2015

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Roll No. P 0412162069

Session: April 2012

Dedicated

To

My Beloved Elder Brother, Md. Almas Mia

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ABSTRACT

Bangladesh lies at the confluence of worlds three major rivers, namely the Ganges, the Jamuna and the Meghna. In Bangladesh, normally four types of flood expressly river flood, flash flood, tidal flood and storm surge flood appear. The Jamuna River is most vulnerable to river flood. As a low lying country, flood occurs repeatedly in Bangladesh and cause tremendous losses in terms of property and life, particularly in the low land areas. At least 20 % areas are flooded every year and in case of severe flood 68 % areas are inundated. Therefore, the study is carried out to develop floodplain extend maps and inundation maps of the Jamuna River. The present study also deals the flood pattern change with time and impact of levee on flood inundation area. One dimensional hydraulic model HEC-RAS with HEC-GeoRAS interface in co-ordination with ArcView is applied for the analysis.

The bathymetric data collected from Institute of Water Modelling (IWM) is used for river grid generation. The collecting DEM from NASA is resampled into 10×10 m resolution. The bathymetric grid has been merged with the topographic DEM to produce the complete DEM of the river. Using this complete DEM, required data sets such as stream centerline, banks, flow paths and cross sections are prepared in HEC-GeoRAS pre-processing option, which are finally imported in HEC-RAS. In HEC-RAS, boundary conditions for upstream and downstream are defined by discharge and water level data respectively. After boundary condition setup, the model calibration and validation are performed using known hydrological data collected from BWDB. Performance of the HEC-RAS models are evaluated using standard and widely used indicators. The coefficient of determination (R^2) has been found as 0.985, 0.977, 0.821 and 0.811 for steady calibration, steady validation, unsteady calibration and unsteady validation respectively. The NSE values have been found greater than 0.60 for both calibration and

validation. After calibration and validation flood inundation and flood hazard map are generated using post-processing of HEC-GeoRAS .

The results of flood frequency analysis by Log Normal method showed discharges of 65772, 76871, 83519, 91299, 96703 and 101790 m^3/sec for 2, 5, 10, 25, 50 and 100-year return periods floods, where Log Normal method is best fitted among the using other methods and used in modeling. The percentages of area inundated by 2, 5, 10, 25, 50 and 100-year return periods floods are 38.28, 46.10, 51.14, 54.63, 56.89 and 59.19% respectively. The flood inundation area increase with the increase of return period. It followed into the log curve $y = 249.84ln(x) + 1789.3$. The classification of flood depth area showed most of the flooding area had water depth between 1.2 m to 3.6 m. The assessment of the flood inundated area showed that 41.99% and 30.83% area are of high hazard and very high hazard respectively for the 100-year return period flood. The flood inundation area's changing pattern with time are studied by five years unsteady simulation flow data at Bahadurabad station. From unsteady simulation, an empirical equation is developed between water level and flood inundation area. The empirical equation is $y = 4.77x^2 - 138.76x + 1008.30$. The levee has impact on flood inundation area. The flood inundation areas decrease with rise of levee elevation . For the 100 year return period, if levee elevation is raised up to 2.13 m from existing levee elevation, then flood inundation land area decreased from 59.19% to 40%. No land will be inundated, if the levee elevation raised up to 2.56 m.

Thus, finding of the study may help in planning and management of flood plain area of the Jamuna River to mitigate future probable disaster through technical approach. Finding of the study may also help to determine suitability of building flood control structure like embankment, detention ponds for prevention purposes. The automated floodplain mapping and analysis using these tools provide more efficient, effective and standardized results and saves time and resources. In future study, this model results can be compared with the studies with SOBEK or HEC-RAS (1D/2D) model results. Flood risk maps, others structures like flood control dam, reservoir impact on flood can be studied in future studies.

Contents

List of Tables

List of Figures

List of Notation and Abbreviations

ArcGIS	Arc Geographic Information System
ARI	Average Recurrence Interval
BMD	Bangladesh Meteorological Department
BTM	Bangladesh Transverse Mercator
BWDB	Bangladesh Water Development Board
CDMP	Comprehensive Disaster Management Programme
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GUI	Graphical User Interface
HEC	Hydrologic Engineering Center
HEC-RAS	Hydrologic Engineering Centre-River Analysis System
HEC-GeoRAS	Hydrologic Engineering Centre-Geospatial River Analysis System
IPCC	Intergovernmental Panel on Climate Change
IWM	Institute of Water Modelling
LAS	Lidar and Surface
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NSE	Nash-Sutcliffe Efficiency
PPCC	Probability Plot Correlation Coefficient
PWD	Public Works Department
RAS	River Analysis System
RMSD	Root Mean Square Deviation
SRTM	Shuttle Radar Topographic Mission
TIN	Triangular Irregular Networks
WARPO	Water Resources Planning Organization
WMO	World Meteorological Organization

Chapter 1

Introduction

1.1 Background and present state of the problem

The densely populated Bangladesh is located in the south Asian sub-continent. Specifically, Bangladesh lies at the confluence of worlds' three major rivers, namely the Ganges, the Jamuna and the Meghna. The country is mostly flat with only a few hills in the southeast and the northeast parts. Generally ground slopes of the country extend from the north to the south and the elevation ranging from 60 meters to one meter above Mean Sea Level (MSL) at the boundary at Tatulia (north) and at the coastal areas in the south (Islam 2012). Bangladesh is one of the most natural disaster prone nations in the world where storm surges, cyclones, floods, river bank erosions, and droughts are frequently occurred (Nasreen 2004). Among natural disasters in Bangladesh, flood is the dominant one. As a low lying country, at least 20 % areas are flooded every year and in case of severe flood 68 % areas are inundated (Disaster Management Bureau 2010). Bangladesh has experienced floods of a vast magnitude in 1974, 1984, 1987, 1988, 1998, 2000 and 2004 (FFWC 2005). The Floods of 1988, 1998 and 2004 inundated about 61%, 68 % and 38% of the total area of the country, respectively (Rahman *et al.* 2007).

Normal floods are considered as a blessing for Bangladesh providing vital moisture and fertility to the soil through alluvial silt deposition in floodplains. Moderate to extreme floods are of great concern, as they inundate large areas and cause widespread, infrastructures damages, including physical damages to agricultural crops, buildings and other infrastructures, social disruptions in vulnerable groups, livelihoods and local institutions, and direct and indirect economic losses. The majority of flood disaster's victims are poor people, who suffer most and are the first casualty of such incidents (WWAP 2006). The flood hazard problem in recent times is getting more and more frequent and acute due to growing population size and human socioeconomic activities in the floodplain at an ever increasing scale. The flood damage was US $ 1.4, 2.0, 2.3, and 1.1 billion in the 1988, 1998, 2004 and 2007 severe flood's year in Bangladesh respectively (World Bank 2007).

Bangladesh generally experiences four types of floods: flash floods, river floods, tidal floods and storm surges floods, nevertheless, vulnerability to these four types of floods varies according to different regions in the country. North-eastern part of Bangladesh is vulnerable to flash flood. Storm surge floods occur in the coastal areas of Bangladesh which consist of large estuaries, extensive tidal flats, and low lying islands. Mainly north-center parts of the country are affected by river flood.

The Brahmaputra-Jamuna River, draining the northern and eastern slopes of the Himalayas, is 2900 km long where in Bangladesh the reach length is 240 km (Bhuiyan *et al.* 2010). The Jamuna one of the dominant rivers of the country where river floods are a common phenomenon. Normally, 25-30% of the area is inundated during monsoon season along the river (Hossain 2003). In case of extreme flood events 50-70% of the country are inundated extending the areas far beyond the riverbanks (Hossain 2003). The causes of Jamuna River floods are heavy rainfall in monsoon, snowmelt, enormous discharge coming from upstream, levee breaching, river siltation etc (Shardul *et al.* 2003, FFWC 2008). The IPCC research reported that Bangladesh is highly vulnerable to climate changes (IPCC 2013). According to IPCC (2013), both monsoon rainfall and sea level will be raised. Because of increased monsoon rainfall and raised sea level, flood inundation will be affected.

The structural and non-structural measures are practiced to control flood in Bangladesh. Embankments, levee, flow regulating structures are operated as a structural measure and flood forecasting and warning, flood proofing, floodplain extend and inundation depth mapping, flood fighting are practiced as non-structural measures to control flood in Bangladesh. The Flood extend and inundation depth mapping are a vital component for appropriate land use planning in flood-prone areas, and optimal exploitation and management of the land and water resources flood inundation.

1.2 Importance and significance of this study

It is essential to understand the characteristics of flood inundation for the Jamuna River. With this study we can know, how much area will will be flooded due to a given discharge. In addition to that, we need to know how fast or at what rate the flood plain areas are flooded due to given discharge, to answer these key questions, this study has been taken.

Though flood inundation modeling requires a two dimensional model, however, study of flood inundation can be done using a one dimensional (1D) hydrodynamic model which includes flood plains as a part of its domain. For example, HEC-RAS and HEC-GeoRAS were being used widely to develop flood inundation map in many studies (Hazarika 2007, Knebl *et al.* 2005, Hicks and Peacock 2005, Abera 2011, Khan 2009). Most of the studies have been done in abroad. Flood extend and inundation depth mapping studies using mathematical model in Bangladesh are limited. In Bangladesh, a few studies have been done using satellite images and GIS (Bhuiyan 2014, Islam *et al.* 2010, Hasan 2006). The accuracy of flood inundation map depend on the water surface elevation. In gis tools providing water surface elevation is difficult. Because it is manual process. The automated floodplain mapping and analysis using HEC-RAS and HEC-GeoRAS tools will provide more efficient, effective and standard results and saves time and resources. The outcome of this study will help the planner to prepare river flood warning maps to reduce the sufferings of people, damage of crops and vegetation, and destruction of infrastructures.

1.3 Research objectives

The overall objective is to study the capabilities of one dimensional hydrodynamic model in simulating flood inundation of the Jamuna River. The followings are the specific objectives of this study:

1. To estimate maximum floods for different return periods.
2. To set up a one-dimensional hydrodynamic model for the Jamuna River which includes flood plains.
3. To generate and compare flood inundation maps by simulating selected known flood events
4. To predict flood inundation maps of the Jamuna River for different return periods.

1.4 Study area

The Jamuna watershed lies in North-Central and North-West Zone of Bangladesh. The Jamuna's middle portion and its floodplain, about 25 km in the left bank and 35 km in the right bank of the river, are the study areas in this study (Fig: 1.1). Its extends between $24^\circ\ 28'26''$ to $25^\circ\ 12'8''$ N latitude and $89^\circ 23'38''$ to $90^\circ 7'30''$ E longitude. The river reach length is about 100 km and the total area is 5858 square km. The study areas have been chosen based on the 1998 flood's inundation area which are the maximum inundation areas of the Bangladesh. Only the Jamuna River's floodplains has been considered for this study which includes the following districts: Gaibandha, Bogra, Sirajganj, Sherpur, Jamalpur and Tangail.

Figure 1.1: Study area

1.5 Thesis organization

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

Chapter one provides the background of the study and present state of the problems. It also draws attention to the objectives of the study, study area and organization of the chapters. Chapter two has the brief description of the Jamuna River and previous studies on flood inundation modeling. This chapter also contains details of flood in Bangladesh, causes of flood and flood management. Chapter three presents review on the HEC-RAS, HEC-GeoRAS hydraulic model and ArcView GIS. Chapter four discusses about data collection, the methodology of frequency analysis. This chapter also discusses the methodology of DTM creation and pre-processing of HEC-GeoRAS. Chapter five describes the results of the calibration and validation of the Jamuna River water level. This chapter also describes the post-processing of HEC-GeoRAS. Chapter six describes the results of flood inundation modeling. Finally, chapter seven concludes the results of the study and provides recommendations for further study.

Chapter 2

Literature Review

2.1 The Jamuna River

The river Brahmaputra-Jamuna is originated in the Himalayas, flowing through China, India and entering Bangladesh through the northern boundary. The Brahmaputra-Jamuna River, covering a basin area of approximately 13330 sq km with in the country premises, is one of the world's greatest rivers, ranking in the top three in terms of both sediment and water discharge (Rajib *et al.* 2011). On the Bangladesh plains the gradients are small and relatively minor changes in land elevation are sufficient to cause dramatic changes in the river course. Natural causes for such changes can be tectonic movements, severe floods caused by tropical monsoons, and extreme sediment loads (Jagers 2003). The Brahmaputra-Jamuna River has a direct and significant influence on the overall water availability of the country (Paul 2014).

2.1.1 General characteristics

The Brahmaputra-Jamuna River draining the northern and eastern slopes of the Himalayas is 2900 km long where in Bangladesh the reach length is 240 km and has a drainage area of 573,500 square km (Bhuiyan *et al.* 2010). In the Bangladesh reach the river has several right bank tributaries, the Teesta, the Dharla, the Dudhkumar and two left bank distributaries the Old Brahmaputra and the Dhaleswary Rivers. It is a wandering braided river with an average bankful width of about 11 km (BWDB 2010). The channel has been widened from an average of 6.2 km in 1834 to 10.6 km in 1992 (FAP16 1995). It has an average surface slope of 7 cm/km (BWDB 2010).

2.1.2 Flow pattern of Jamuna River

The Jamuna River has an average annual discharge of 19,600 m3/sec and the river drains an estimated 620 billion cubic meter of water annually to the Bay of Bengal and 80% of this flow passes during june to september, to the sea which if impounded on our flood plain would have about 9 meters deep standing water (Islam 2012). Over the years, due to the sedimentation on the river bed and lack of proper dredging facilities, the Bangladeshi rivers conveyance capacity has been reduced. The discharge varies from a minimum of 3,000 cumec to a maximum of 100,000 cumec, with bankful discharge of approximately 48,000 cumec (Islam 2012).

A picture of the annual flow cycle of the Jamuna River at Bahadurabad gauge station is presented in the figure: 2.1. The Jamuna River's maximum discharge, approximately

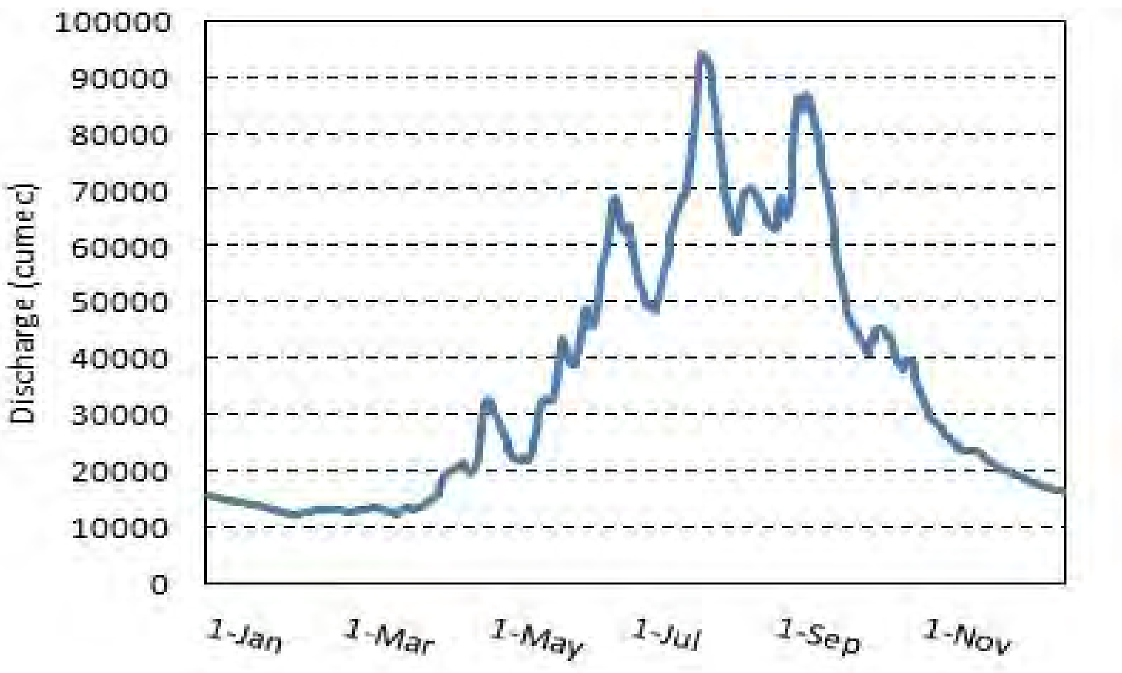


Figure 2.1: Typical discharge of the Jamuna River at Bahadurabad for 2007

64% of total discharge, occurred during July to September.

2.1.3 Rain fall distribution

The main source of Brahmaputra River is Yarlung Tsangpo in southwest Tibet which has a considerable catchment in huge canyons and subsequently Arunachal Pradesh

(India) that penetrates in Himalayas. The river is called Dihang in Arunachal Pradesh (India). This river runs through Assam basin which is named as Brahmaputra and toward the south though Bangladesh this river is known as Jamuna (Paul 2014). The catchment of the mighty Brahmaputra-Jamuna River is about 5,83,000 sq km of which 293,000 sq km are in Tibet, 241,000 sq km in India and only 47,000 sq km within Bangladesh. The Brahmaputra occupies eighth position in a list of 34 major rivers of the world on the basis of their annual average runoff (Paul 2014). The mean of monthly rainfall pattern on the context of Bangladesh has been calculated using 64 years (from 1950 to 2013) rainfall data at Bogra gauge station (figure 2.2). The catchment is characterized by a rainfall which amounts from 1058 mm to 2601 mm per year. These highest rainfalls were experienced during the months June, July, August and September. The rainfall distribution over the catchment is nearly 73.23% of the annual rainfall occurs in monsoon period. This huge precipitation results flooding in the monsoon season.

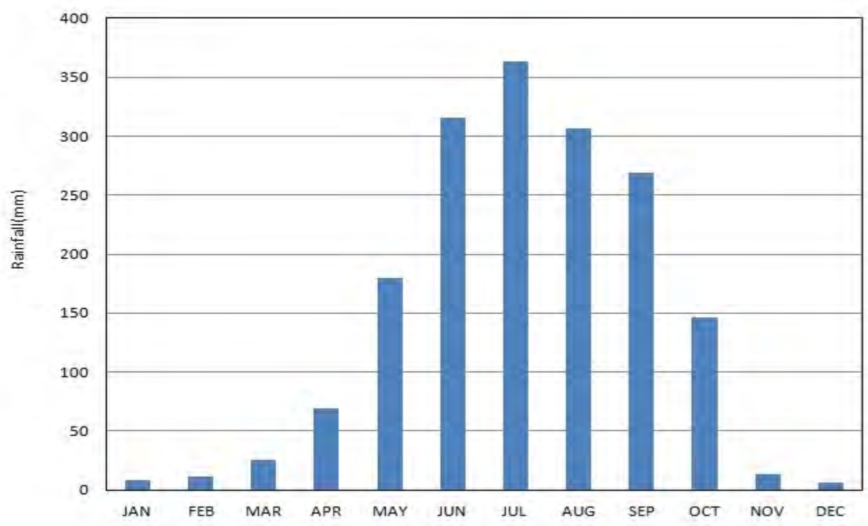


Figure 2.2: Mean monthly rainfall pattern of the Jamuna River catchment from 1950 to 2013

2.2 Previous studies

2.2.1 Previous studies on flood mapping

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.

Efforts have been made to collect and review the thesis reports, journals, books, tools user manuals. A outline of some of the reports is given below:

Hazarika (2007) studied capacity building in application of informatics in flood hazard mapping. He studied flood projects in Bangladesh, China, Cambodia, and Nepal. He explained a detail flood hazard map in Cambodia. Study reach was Nekong river basin which covered 3 provinces, 26 districts, 305 communes with 245086 populations. His main objective of the study was preparing hazard maps using depth map and the socio-economic data. In his study he used radersat satellite image of September and October 2000. He used discharge and water level data from 1991 to 2002 and manning's roughness coefficient of river and floodplain from land use map. He prepared flood depth map using HEC-RAS and GIS and also the flood hazard map. He also studied flood forecasting and early warning system in Bagmati river floodplain. He prepared flood map and tabulated inundation areas. He analyzed the flood duration and crop damages. He prepared flood map for 6 return period of 2, 5, 10, 20, 50, and 100 year. He showed inundation area ranging from 363 to 465 sq. km. which is 37% to 47% of the district area.

Knebl *et al.* (2005) studied regional scale flood modeling using GIS, HEC-HMS, and HEC-RAS in San Antario river basin summer 2002 storm event. They developed a framework for regional scale flood modeling that integrates NEXRAD Level III rainfall, GIS, and a hydrological model (HEC-RAS/HMS). The san Atonio river basin (about 10000 sq. km.) in Central Texas, USA, was the domain of the study because it was a region subject to frequent occurrences of severe flash flooding. A major flood in the summer of 2002 was chosen as a case to examine the modeling framework. The model consisted of a rainfall-runoff model (HEC-HMS) that converted precipitation excess to overland flow and channel runoff, as well as a hydraulic model (HEC-RAS) that models unsteady state flow through the river channel network based on the HEC-HMS derived hydrographs. HEC-HMS was simulated on a 4X4 km grid in the domain, a resolution consistent with the resolution of NEXRAD rainfall taken from the local river authority. Watershed parameters were calibrated manually to produce a good simulation of discharge at 12 sub basins. With the calibrated discharge, HEC-RAS was capable of producing floodplain polygons that were comparable to the satellite imagery. The modeling framework presented in this study incorporated a portion of the recently developed GIS tool named ArcView that had been created on a local scale and benefit future modeling efforts by providing a tool for hydrological forecasts of flooding on a regional scale. While designed for the San Antonio river basin, this regional scale model might be used as a prototype for model applications in other areas of the country.

Hicks and Peacock (2005) studied the suitability of HEC-RAS for flood forecasting. They found that most river flood forecasts were conducted using a two-step procedure. First, flood routing was conducted, normally using hydrological models. The resulting flood peaks were then converted to water level forecasts using a steady flow hydraulic model, such as HEC-RAS. The HEC-RAS model had been extended to facilitate unsteady flow analysis, and while the numerical scheme was not robust enough to handle dynamic events (such as ice jam release floods) or supercritical flows, it did have the capability to route simple open water flows and produce water level forecasts at the same time. Here, the viability of the HEC-RAS unsteady flow routine for flood forecasting was examined through an application to the Peace river in Alberta and it is shown that accuracy comparable to more sophisticated hydraulic models can be achieved. Since many agencies already have HEC-RAS models estabilished for floodplain delineation purposes, it would be simple matter to extend them to the flood forecasting application. They thought an ancillary advantage would be that flood forecasting accuracy could potentially be improved and simplified into a one-step process, without necessitating a time-consuming transition to unfamiliar models.

Hatipoglu *et al.* (2007) studied on floodplain delineation in Mugla-Dalaman plain using GIS based river analysis system. In his study, an application of HEC-RAS and HEC-GeoRAS model ware applied in Mugla-Dalaman floodplain. Due to its economic and touristic potential, Dalaman floodplain is very important. They studied that area before and delineated the floodplain with traditional methods and found the houses and lands of the local people prices were decreasing because of being in the flood plain. For the determination of flood-plain, first, HEC-RAS simulations were performed to generate water surface profiles throughout the system. Floodplain zones for the design storms were reproduced in three dimensions with HEC-GeoRAS by overlaying the integrated terrain model for the region with the corresponding water surface TIN. As a result it was seen that the floodplain extend that was found by GIS based methods gives considerable better results than by traditional methods.

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 4.7 m 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.

Bhuiyan (2014) studied the flood hazard and vulnerability in a riverine flood prone area. He used Remote Sensing (RS) and Geographic Information System (GIS) to evaluate the flood hazard and vulnerability. He used flood frequency analysis to assess flooding for different flood magnitudes. He prepared flood map and hazard map for 6 return period 2.33, 5, 10, 25, 50 and 100. He found inundation areas ranges from

1250 to 2500 acres which is 23% to 50% of the total area. He also found in 100-yr return period 51.71 percent land became inundated, in which F0, F1, F2, F3 and F4 inundation areas were 6.47, 11.45, 5.78 and 16.14 acres respectively.

Alaghmand *et al.* (2012) studied gis-based river basin flood modeling in Kayu Ara river basin. HEC-HMS, MIKE11 and GIS was used in river basin flood modeling. The hydrologic model like HEC-HMS was used to develop rainfall-runoff from a design rainfall or historic rainfall event. The MIKE11, hydraulic model, was used to routes the runoff through stream channels to determine water surface profiles (including depth and velocity) at specific locations along the stream network. Finally, ArcGIS was used to process and visualize the river flood extent map, river flood depth distribution map, comparison map and river flood duration map. They were found increase of rainfall event ARI (average recurrence interval) from 20 year to 100 year causes 29% increase in the river flood inundated area. They also were found increase of rainfall event ARI from 20 year to 100 year, inundated area with 0 cm to 100 cm depth is increased from 10.36 hectares to 14.40 hectares.

Duvvuri and Narasimhan (2013) studied flood inundation mapping of Thamiraparani river basin using HEC-GeoRAS and SWAT model. They 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. They 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. They also studied the impact of levees on flood extent and inundation depth. They found that accurate location of levees is highly critical in controlling the inundation and lessens the extent of damage.

Abera (2011) studied flood mapping and modeling on Fogera flood plain. HEC-HMS, HEC-RAS and HEC-GeoRAS ware used in river basin flood modeling. He found a flow value of 91.8, 202.4, 273.1, and 308.4 cumec 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 year was 12.63, 18.63, 21.31 and 22.5 sq.k respectively. He found most of the area flood depth is less than 1.5 m. He also found 88% of agricultural land, 11.6% of agro-pastoral land and 1.36% river inundated by the flood.

Islam *et al.* (2010) studied flood inundation map of Bangladeshu 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.

2.3 Floods in Bangladesh

2.3.1 Floods and its types

The term flood is generally used when the flows in the rivers and channels can not be contained within natural or artificial river banks. By spilling the river banks, when water inundates flood plains and adjoining high lands to some extent or when the water level in the river or channel exceeds certain stage, the situation then termed as flood. In Bangladesh, the following types of floods are normally encountered. Area affected by different types of flooding is presented in figure: 2.3

Riverine and rainfall flood

The word flood is generally synonymous with the river flood. Cross-boundary inflow, coincidence of the flood peaks of Ganges, Brahmaputra and Meghna and huge rainfall are the cause to occur this type of flood in Bangladesh. Of the total flow, around 80% occurs in the 5 months of monsoon from June to October (WARPO 2004). A similar pattern is observed in case of rainfall also. In the middle of the country, a broad strip of land is flooded by bank overflow from the main rivers - Jamuna, Ganges, Padma, and Meghna, and their tributaries and distributaries. Heavy rains also cause flooding, as drainage is impeded by high stages in the main rivers. Normally, 20-25 % of the area

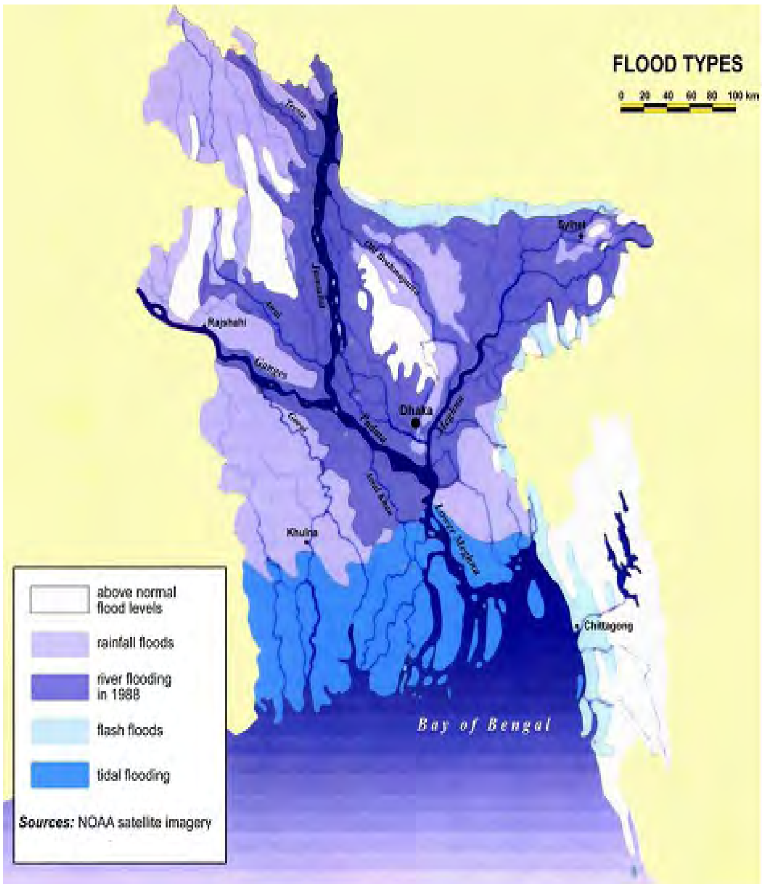


Figure 2.3: Types of flood in Bangladesh (Source: Rahman *et al.* 2005)

is inundated during monsoon season along the river. In case of extreme flood events 35-70% of the country is inundated extending the areas far beyond the riverbanks. This type of flood becomes disastrous when the flood peaks of the Ganges, Brahmaputra and Meghna synchronize within a week or so, as was the case during the catastrophic floods of 1988 and 1998.

Flash flood

A flood, which is caused by heavy or excessive rainfall in a short period of time over a relatively small area, is called flash flood. Typically, flash floods occur in areas where the upstream basin topography is relatively steep and the concentration time of the basin is relatively short. In Bangladesh flash floods generally occur in the north-east, south-east and Chittagong region. But devastating and extended flash flood is a recurrent phenomenon for the north-east region of Bangladesh. The extreme flashy character of the rivers and sudden excessive rainfall in the region cause frequent flash floods in the north-eastern Haor areas. In the Haor area, flash flood comes from the very steep uplands adjacent to the region in Asam and Meghalaya hills range in India, causing immense damage to the standing boro crops, lives and properties every year.

Tidal flood

Bangladesh faces semi diurnal tide i.e., two flood tide and two ebb tide in a day in an 6 hour consecutive time interval. Coincidence of heavy rainfall and flood tide occurred water logging in urban area located in coastal part of our country during monsoon. In Chittagong city in Chaktai and Moheshkhali khal catchments such type flood is a common phenomenon in every year monsoon.

Cyclone and storm surge flood

In Bangladesh, most of the cyclones occur during the pre monsoon (April, May, and early June) and post monsoon (late September, October, and November) periods. The pre monsoon period is the sowing or broadcasting season for Aus rice and the post monsoon season is the harvesting season for Aman rice in the coastal areas. Some of the greatest disasters in the history of the world have occurred in the Bay of Bengal. During the period 1877 to 1978 a total of 1050 depressions formed in the Bay of Bengal of which 254 turned into cyclones and 158 into severe cyclones. 01 November 1876, 24 September 1919, 29 May 1963, 11 May 1965, 12 November 1970, 29 April 1991, 15 November 2007 (SIDR), 25 May 2009 (AILA) are the major cyclones occurred in our country. During cyclone water entered into the coastal areas and polders by storm surge creates severe flooding caused damage to crops, livestock and house-holds.

2.4 Causes of flooding

The causes of flooding can be divided into two categories:

1. Short-term causes, and 2. Long-term causes

2.4.1 Short-term causes

High Monsoon flow through the principle channels

Flood can cause from an increased amount of precipitation. The primary cause of the flood in Bangladesh is downpour in the monsoon period in the Ganges-Brahmaputra-Meghna drainage basin system. Around 80% flow and rainfall occur in the 5 months of monsoon from June to October. As a consequence to these skewed temporal distribution of river flow and rainfall, Bangladesh suffers from abundance of water in monsoon, frequently resulting into floods. Climatologically, the discharge into Bangladesh, from upper catchments, occurs at different time of the monsoon. In the Brahmaputra maximum discharges occurs in early monsoon in June and July whereas in the Ganges maximum discharge occurs in August and September. Synchronization of the peaks of these rivers results in devastating floods. Such incidents are not uncommon in Bangladesh. The rivers of Bangladesh drain about 1.72 million sq km area of which 93% lies outside its territory in India, Nepal, Bhutan and China. The annual average runoff of the cross boundary rivers is around 1200 cubic kilometres (WARPO 2004). Maximum and minimum flood discharge in the main rivers are shown in figure 2.4

Levee breach

Levee breach flood disaster is one of the common natural hazards in Bangladesh. During flooding season, large amount of water flows through Bangladeshi river and it causes earthen levee breach and its failure cause flooding inside the levee and huge damage occurs in the inhabitants insides the levees. Failure of levees not only increases the siltation in the river beds and floodplains but it causes huge damage in agricultural production, residents, roads and other (Islam and Tsujimoto 2011). During the rainy seasons (June to September), nearly a trillion cubic meter of water laden with about two billion tons of silt passes through the main rivers, its come from upstream catchment in India, Nepal, Bhutan and China. These sediments settle over the river beds, floodplains and low lying areas during the inundation and with the recession of flood water. As a result river channels and their distributaries are silted up with sediments composed of fine sands and silts causing drainage congestion and overbank flow resulting in river embankment failure(Islam *et al.* 1994).

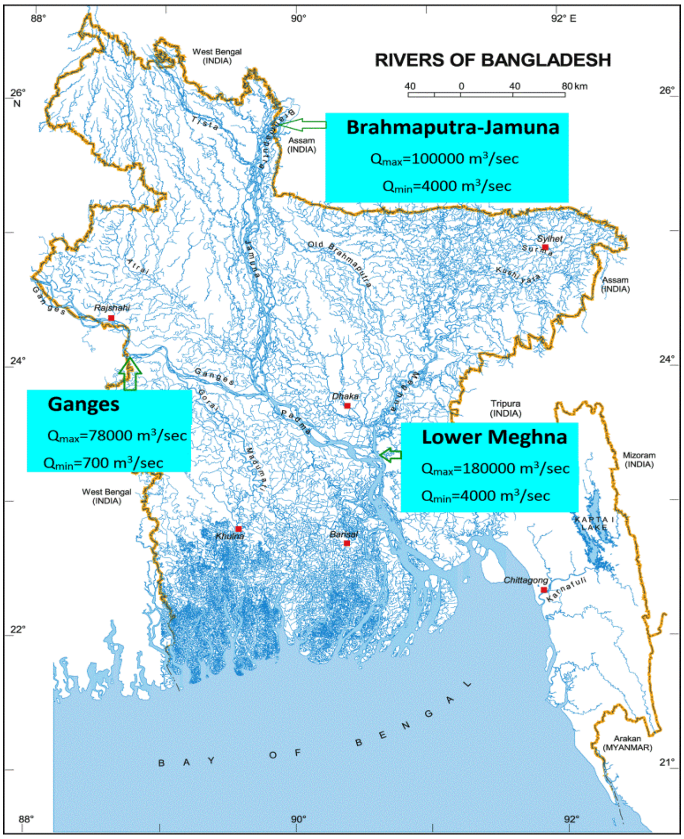


Figure 2.4: Flood discharge in the main rivers (adapted: http://lib.pmo.gov.bd /maps/images/bangladesh/Rivers.gif)

Synchronization of flood peaks

For the major three rivers the synchronization of flood peaks took place within a two week time period, a sudden increase in water level in virtually all areas of the country reduces the water carrying capacity of the drainage system and decreases land elevation with respect to the base level of the rivers in Bangladesh.

2.4.2 Long-term causes

Geographical position

Bangladesh is surrounded on the east, north, and west by India, by Myanmar on the south-east and by the bay of Bengal on the south. Being a low lying country surrounded by hills on its two sides. Figure: 2.5 shows the geographical position of

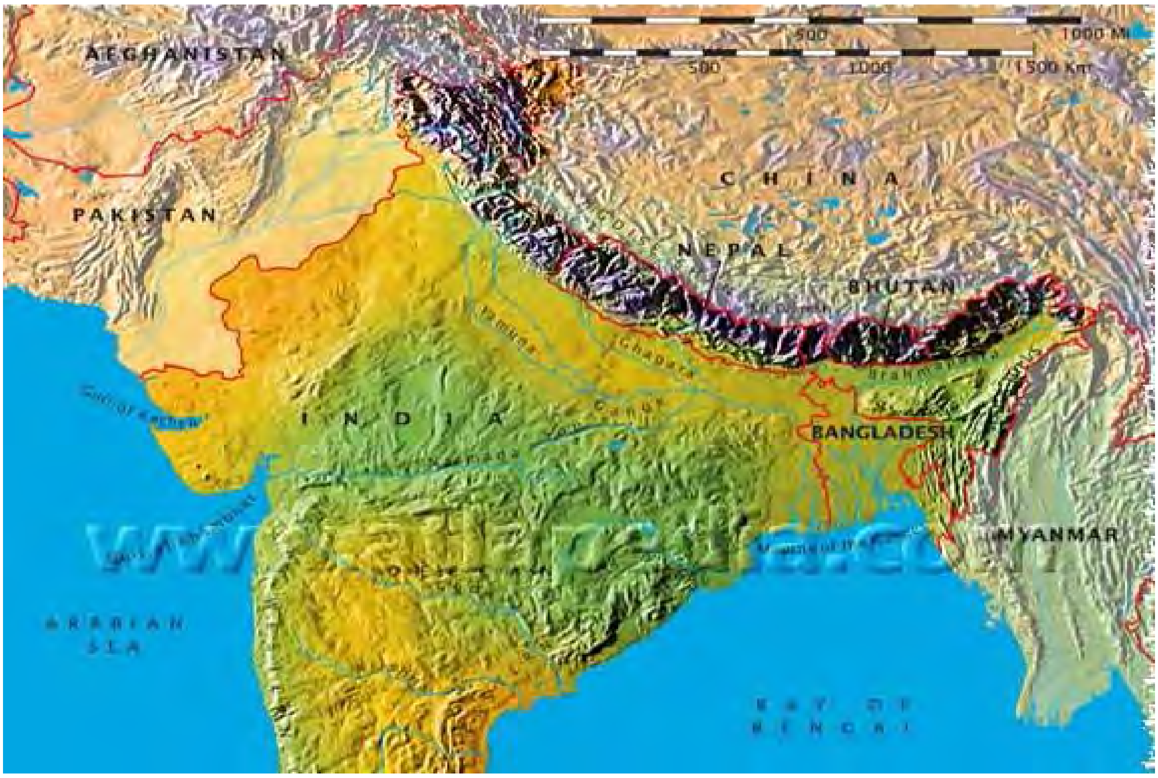


Figure 2.5: Geographical location of Bangladesh (Source: http://www.atlapedia.com)

Bangladesh. The aerial extent of flooding within Bangladesh is principally related to the unique physiographic feature of the country, which is the extensive floodplains of the major rivers and their tributaries and distributaries that cover 80% of the country. The downstream control that exacerbates the flooding condition is offered by the Lower Meghna river, which acts as the single drainage outlet of the three major river systems that carry almost the entire flood flow, and is perennially influenced by tidal back water flow.

Low general topography

The topography of Bangladesh is very low laying in general. About 50% of the country is within 6-7 m of mean sea level (MSL) and 68 % of the country is vulnerable to flood. During the normal flood 25 to 30% of the area is inundated (Khan 2009). Fig: 2.6 shows the Land topography of Bangladesh.

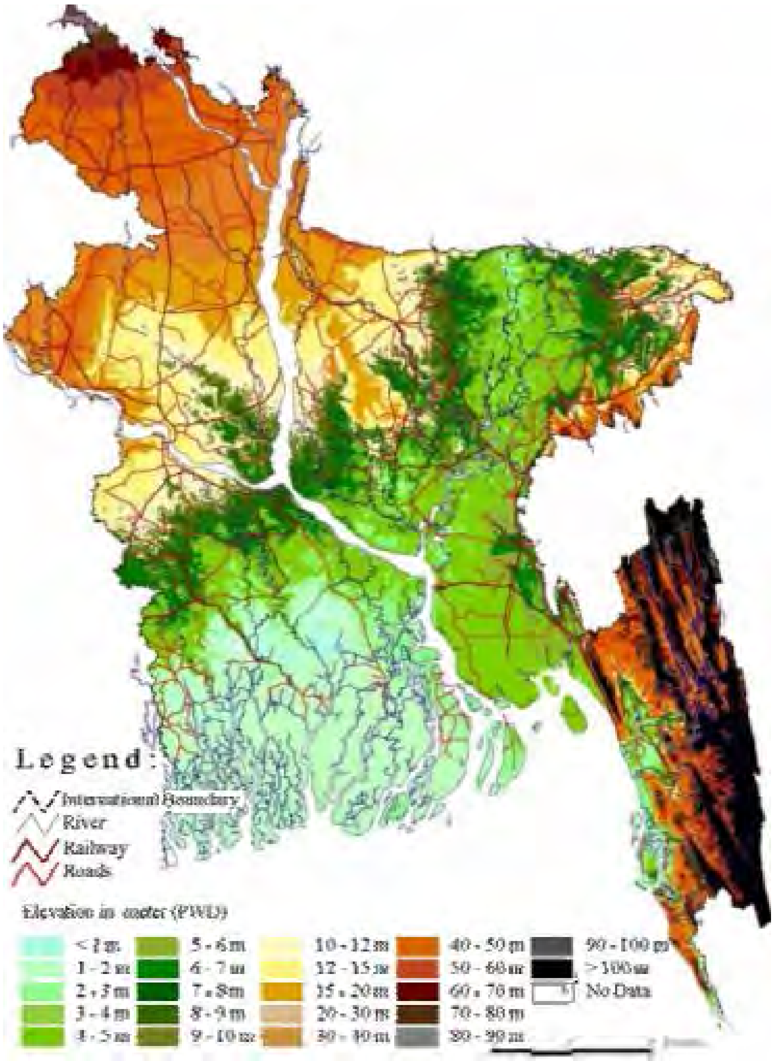


Figure 2.6: Land topography of Bangladesh(source: http://www.spp-j.com/spp/1-1/spp.2014.12A0001)

Transboundary rivers and outside catchment area

The headwaters of the Ganges's and Brahmaputra originate from the Tibet of China area of the Himalayan Mountain range. The Ganges river flows south-west into India, turns southeast joining with major tributaries. After flowing into Bangladesh, the Ganges joins with the Brahmaputra and Meghna river to flow into the Bay of Bengal as the Meghna (Padma) river. The Brahmaputra flows eastwards in the Tibet then turns south and west into India and then directs south into Bangladesh. Together the Ganges, Brahmaputra and Meghna basins, one of the largest river basin systems of the world, cover approximately 1.7 million square km, including Bhutan, north-western India, Nepal and Tibetan China, which around 12 times Bangladesh's land area. There are 57 trans-boundary rivers of which 54 from India and 3 from Myanmar (Khan 2009). The Brahmaputra-Jamuna, the ganges and the Meghna rivers basin are shown in figure

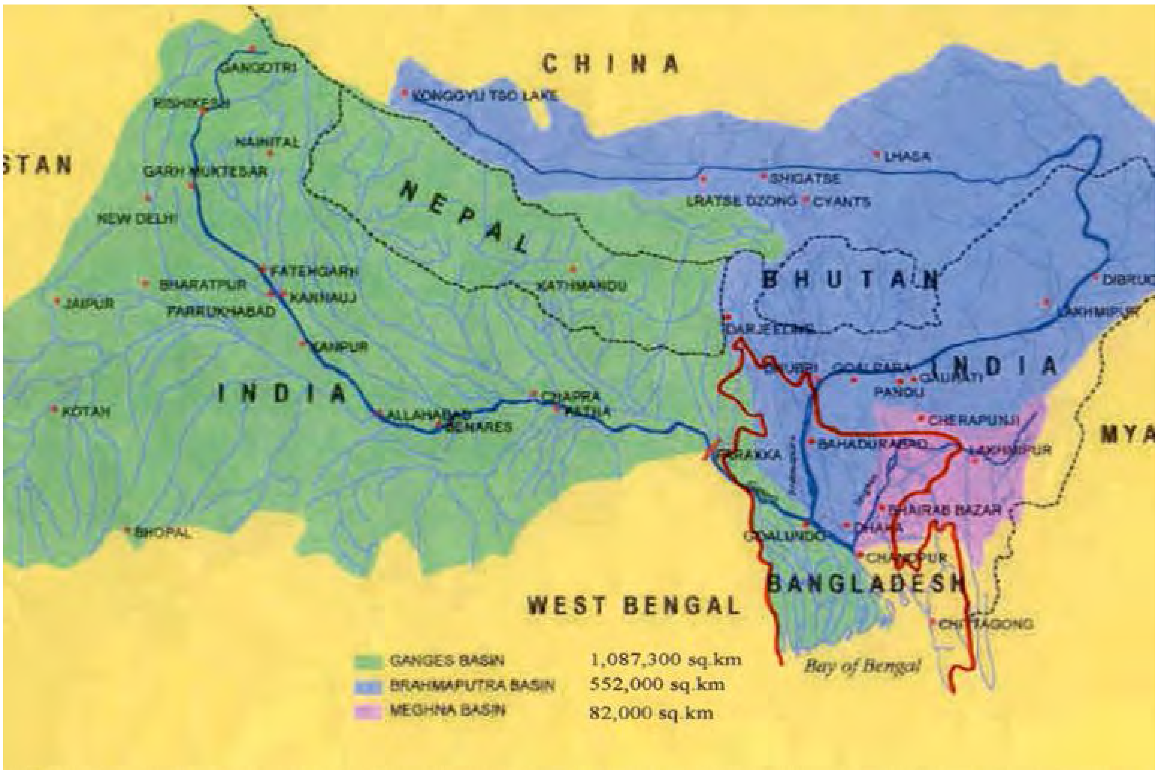


Figure 2.7: The Ganges-Brahmaputra-Meghna basins

2.7.

Sea level rise

The Ocean is the final destination of all the rivers. With respect to sea level in an area the land elevation is measured. Therefore, any change in sea level causes land elevation to change. Sea level is rising globally at the present time and if it rises in an area at a rate faster than the rate of land aggradations 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 (CEGIS 2007). 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 accumulation of river water inland which certainly seems to be one of the reasons for the increase in flood intensity in Bangladesh in recent years (Khan 2007).

Compaction and subsidence of sediments

On a delta plain, sediments 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. 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.

River bed aggradations

The large-grained sediments are deposited near the source area on the river beds due to relatively higher settling velocity, forming sand bars. If sedimentation continues on the riverbeds the river gradient decreases rapidly because of low gradients and high sediment loads, the riverbeds of most of the rivers in Bangladesh aggregate very quickly. River bed aggradations are most pronounced for the Ganges and its distributaries. River bed aggradations reduce the water carrying capacity of rivers, causing them to overflow their banks and it is so pronounced in Bangladesh that changes in river bed level can be observed during one's lifetime.

Rivers damming

River damming 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 aggradations and in turn reducing the water carrying capacity of the river. The Farakka Barrage (river barrier between Bangladesh and India) on the Ganges has already caused tremendous damage to the agriculture, navigation, environment, and hydrodynamic equilibrium in Bangladesh (Khalequzzaman 1994).

Climate change

Scientists assumed that the flood increased as the world gets warmer, which is absolutely true as the world is about to enter a period of rapid warming. Owing to global warming in the north pole snow is melting, which is responsible for sea level rise. Rising sea level of even greater magnitude will cause flood on the low land and slow the speed at which rivers can remove water from the land. Bangladesh will be severely impacted by such an increase in sea level. Besides many other adverse environmental, economic, and climatic consequences, the base level of all rivers will change following any change in the sea level. The greenhouse effect will cause frequent cyclone as a result of high temperature will lead to flood problem and the rainfall could increase by 10% to 15% by the year 2030 (Climate Change Cell 2009).

2.5 Statistics of flood and its effects

Bangladesh is one of the most flood-prone countries in the world. The literature on floods in the country is extensive. Due to its location in the low-lying deltaic floodplains at the convergence of three Himalayan Rivers, heavy monsoon rain-fall concomitant with poor drainage often results in annual flooding. Bangladesh experiences floods almost every year with considerable damage. The floods of 1954, 1955, 1974, 1987, 1988, 1998, 2004 and 2007 all caused enormous damages to properties and considerable loss of lifes (FFWC 2008). Flood statistics for Bangladesh are summarized in table 2.1.

The catastrophic flood of 1987 occurred throughout July and August and was estimated as a once in 30-70 year event. The flood's main cause was the creation of Erranticophrus (top soil wash away reaction) from the inhabitants of the Himalayas irrigating their mountains vertically. 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 (Hossain 2003).

The flood of 1988, which was also of catastrophic consequence, occurred throughout August and September. The flood return period was estimated at 50-100 years. Rainfall together with synchronisation of very high flows of all the three major rivers of

Table 2.1: Year-wise flood affected area in Bangladesh (source: FFWC 2008)

Year	Flood affected area		Year	Flood affected area		Year	Flood affected area	
	Sq. Km	%		Sq. Km	%		Sq. Km	%
1954	36,800	25	19,73	29,800	20	1991	28,600	19
1955	50,500	34	1974	52,600	36	1992	2,000	1.4
1956	35,400	24	1975	16,600	11	1993	28,742	20
1960	28,400	19	1976	28,300	19	1994	419	0.2
1961	28,800	20	1977	12,500	8	1995	32,000	22
1962	37,200	25	1978	10,800	7	1996	35,800	24
1963	43,100	29	1980	33,000	22	1998	1,00,250	68
1964	31,000	21	1982	3,140	2	1999	32,000	22
1965	28,400	19	1983	11,100	7.5	2000	35,700	24
1966	33,400	23	1984	28,200	19	2001	4,000	2.8
1967	25,700	17	1985	11,400	8	2002	15,000	10
1968	37,200	25	1986	6,600	4	2003	21,500	14
1969	41,400	28	1987	57,300	39	2004	55,000	38
1970	42,400	29	1988	89,970	61	2005	17,850	12
1971	36,300	25	1989	6,100	4	2006	16,175	11
1972	20,800	14	1990	3,500	2.4	2007	62,300	42.21
2008	33,655	22.80						

the country in only three days aggravated the flood. Dhaka, the capital of Bangladesh, was severely affected. The flood lasted 15 to 20 days (Dewan *et al.* 2003).

The 1998 flood in Bangladesh were unusual, however, for both their depth and duration. Unlike the normal floods, which cover large parts of the country for several days or weeks during july and august, the floods in 1998 lasted until mid-September in many areas, killing hundreds of people and destroying roads, houses, crops and others assets (Islam and Chowdhury 2002).

The 2004 flood in Bangladesh started with the uncommonly early flash flood with unusual magnitude in Sylhet Basin that occurred in the 2nd week of April causing total damage to the standing crops in the haors. Subsequently, Sylhet basin was heavily flooded again and again. The heavy monsoon river flood of 2004, the 4th major flood in a span of 17 years, arrived in the country in July, again very early for such floods. Almost 40% of the country was inundated during the peak flood, causing tremendous human sufferings and considerable damage. Tidal flood swamped Patuakhali, Jhalkathi and Barisal districts in the southern region in early August. An abnormal depression in the second week of September caused rainfall floods in the central region, and flash floods in the south-western and eastern regions (Rahman *et al.* 2005).

The 2007 flood came in two waves. The first wave commenced around the 24^{th} July 2007 and initially affected Nilphamari, Lalmonirhat and Kurigram, Sherpur, Jamalpur, Sylhet, Sunamgonj districts. In following days Rangpur Gaibandha, Bogra, Sirajganj districts were flooded, and subsequently the other districts were inundated up until about the 6^{th} August. This wave flooded about 39 districts. The second wave commenced on the 5^{th} September and continued up until the 15^{th} September 2007 when some new districts apart from the previous 39 were flooded. A total of 46 districts were affected to varying degrees during both flood waves. Eighty five thousand houses were completely damaged, while almost one million suffered partial damages. The 649 persons were reported to have perished either as a direct impact of the flood or through flood related causes including bridge collapse or boat capsizing. A number of children drowned as a result of swimming in flood areas. A number of people in addition to

Table 2.2: Comparison of losses resulting from recent large floods (source: World Bank 2007)

Item	1988	1998	2004	2007
Inundation area of Bangladesh (%)	60	68	38	42
People affected (billion)	45	31	36	14
Total deaths (people)	2,300	1,100	750	1,110
Livestock kiled (nos)	172,000	26,564	8,318	40,700
Crops fully/partly damaged (milion ha)	2.12	1.7	1.3	2.1
Rice production losses (million tons)	1.65	2.06	1.00	1.2
Roads damaged (km)	13,000	15,927	27,970	31,533
Number of homes fully/partly damaged (million)	7.2	0.98	4.00	1.1
Total losses: Tk(billion)	83	118	134	78
US$ (billion)	1.4	2.0	2.3	1.1

this perished as a result of diseases caused by contaminated water and poor sanitation (Disaster Management Bureau 2007).

Annual regular flooding has traditionally been beneficial, providing nutrient-laden sediments and recharging grounding water aquifers; while low frequency but high magnitude floods can have adverse impacts on rural livelihoods and production. About 26 percent of the country is subjected to annual flooding and an additional 42 percent is at risk of floods with varied intensity. Table 2.2 summarizes statistics from some recent large floods in the country (World Bank 2007).

Typical hydrographs of major flood years are shown in figure 2.8.

2.6 Flood management

Flood is a natural phenomenon which can't be prevented in Bangladesh. The flood control measures and policies are to be directed to mitigate of flood damage, rather than flood prevention. Flood control measures are broadly divided into direct or structural and indirect or non-structural measures.

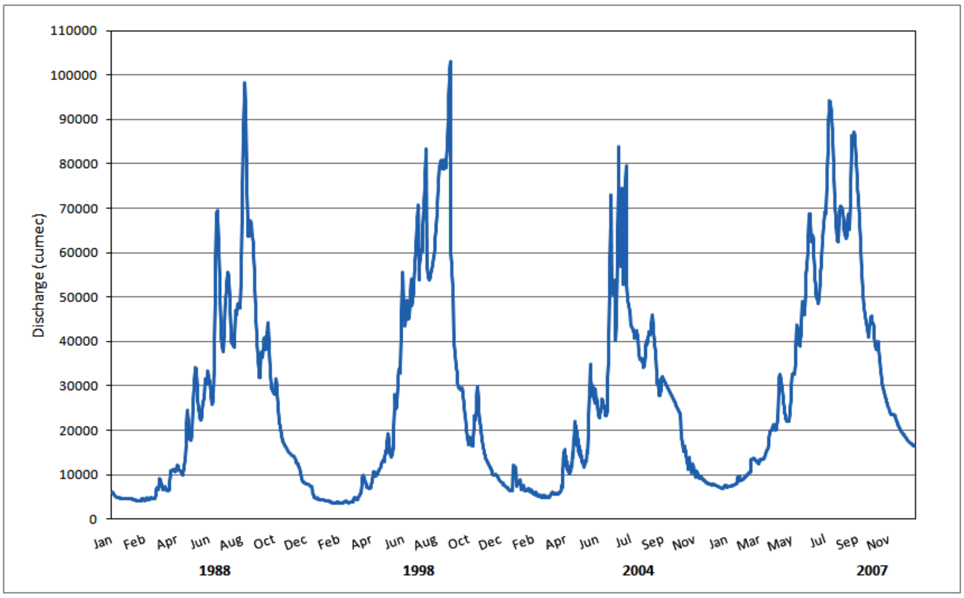


Figure 2.8: Typical hydrographs of major flood years at Bahadurabad gauge station

2.6.1 Structural measurements

A measure to control the physical process of flooding is called structural measurement. It also prevents inundation. Structural measurements are taken to protect vulnerable area up to a certain level of flooding and creates a better condition for increasing productivity of land.

Flood control dams and reservoirs

Flood control dams store all or a portion of the flood waters in the reservoir, particularly during peak floods and then release the water slowly. Typically, the principal use of such dams is to store a portion of the flood volume, in order to delay and attenuate flood peaks downstream. Space within a reservoir is generally reserved to store impending floods. Based on hydrological forecasts, the reservoir is regulated in a way to minimize the chances of coincident peaks from floods in different tributaries synchronizing in the main stem of the river downstream. Small to medium floods, generating from the catchment are fully captured by the reservoirs. However, extreme flood events are only partially attenuated and their transformation downstream is delayed. The extent of attenuation depends on the available storage capacity of reservoir and the magnitude of the flood event (World Commision 2000).

Levee and embankment

Levees (also referred to as Embankment or dykes in some countries) are constructed mainly from earth and used to confine stream flow within the specified area along the stream, or to prevent flooding due to sea waves or tides. Levees should be resistant to hydrostatic pressure of floods, erosion, piping failure and seepage. Further, river protection works such as spurs, studs, revetments, etc., are attached in combination with levees to fulfill those objectives. Since early times, levees have played a vital role in protecting people on flood plains against frequent flooding and continue to be the most favored flood management options.

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 revetting the channel. Large wood pieces embedded in the river bottom cause 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 2006).

Bypass and diversion channels

Bypass channels divert river flows from a point upstream of an area requiring protection. These diverted flows can be discharged back to the same river, here in referred to as a bypass channel, or into another natural drainage system. Flows into bypass and diversion channels are regulated by gates. Functioning of a bypass channel depends mainly on its location, length, carrying capacity and inlet characteristics. While a bypass channel reduces flood magnitude in the bypassed area, it may increase flooding farther downstream, as flood waters are rushed through the bypass channel. A diversion channel can increase the possibility of flooding in the receiving drainage system downstream if the diverted flows are larger than its carrying capacity. Detention or retention basins, constructed in conjunction with the bypass system, can avoid such situations.

2.6.2 Non-structural measurements

Structural measures can never completely eliminate the risk of flooding. Nevertheless, because of their physical presence, they have the potential to create a false sense of security, leading to inappropriate land use in the protected areas. Non-structural measures play an important role in reducing not only the catastrophic consequences of residual risks, but also adverse impacts on the environment.

Flood forecasting and warning

Of all the non-structural measures, flood forecasting and warning is the most widely accepted and has been used since the latter half of the 20th century. It supplements almost all other structural as well as non-structural measures. Flood forecasting involves estimating when a flood is likely to cause damage or loss of life, what its magnitude will be (usually in terms of its maximum stage at a given location) and how long it will last. Flood forecasts are formulated and issued with a certain lead time, allowing concerned authorities to take preventive and emergency measures. Authorities can respond to appropriately with dam operations, opening and closing the gates of various flood management structures, anticipatory releases to increase reservoir storage capacity, etc. The effectiveness of a flood forecast and warning system is as much a function of the accuracy, time-liness and outreach of the forecast as of the response behavior and preparedness. Inflow forecasts for reservoirs, detention basins, bypass channels, etc., play an important role in flood peak alleviation.

Flood proofing

Where the extent of present development is substantial, alternate strategies such as flood proofing can be considered. Flood proofing, a combination of long-term, non-structural 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. Flood proofing measures include, among others, removing goods, equipment and harmful industrial, agricultural and domestic chemicals, beyond the area subject to flooding or out of contact with flood waters, by constructing high ground or small embankments. Existing facilities for drinking water supply have the potential to get contaminated. The sewerage disposal and treatment infrastructure located in the flood plains can cause nuisance and spread of diseases and pollution, affecting the health of the population. Provision should be made for the protection of such infrastructure.

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 and flood hazard mapping

Floodplain inundation and hazard mapping are 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 will provide users more awareness of the flood hazards in their local community. Combined with river observations and weather forecasts, inundation maps will provide decision makers additional information needed to mitigate the impacts of flooding and build more resilient communities. Flood hazard maps provide flood hazard information in terms of the relationship between the flood probability and flood intensity. Such maps should be produced for areas where flooding could cause considerable damage.

Evacuation

Evacuation is an ultimate measure of flood defense, aiming to save human and animal lives and to reduce losses in goods and property. It can take place before, during and after the flood, depending upon the circumstances. Evacuation is essential where the buildings or other features do not provide a safe place of refugee during a flood. In Bangladesh, there is an institutional arrangement for flood preparedness under a national guideline entitled "Emergency Standing Order for Flood".

Emergency assistant and flood relief

Emergency assistant and flood relief aimed at relieving the distress of the flood victims by the announcement of financial and other aids. At the international level, the United Nations Disaster Relief Coordinator has a fund from which money can be drawn to assist victims of disastrous floods. In the contest of climate change government should preserve a good volume of money to assistant and flood relief as an adaptive measure.

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.

Chapter 3

Models and Tools

3.1 Introduction

There are a number of commercial and non-commercial software tools available for numerical modeling and analysis in GIS. The major tools used in this method are one-dimensional numerical model HEC-RAS and ArcView GIS for spatial data processing and HEC-GeoRAS for interfacing between HEC-RAS and ArcView GIS. HEC-RAS and HEC-GeoRAS, a open source model which have excellent Graphical User Interfaces (GUI), were developed by U S Army Corps of Engineers. ArcView GIS was developed Environmental Systems Research Institute (ESRI) which enables to view, edit, create, and analyze geospatial data. Descriptions of these software tools are presented below.

3.2 ArcView GIS 9.3

Introduction

ArcView GIS developed by Environmental Systems Research Institute (ESRI) is a powerful and easy tool to create and use maps, view spatial data and perform spatial analysis. ArcView GIS is equipped with excellent graphical user interface (GUI), which enables visualization, exploring and the analysis of spatial data. All the activities in ArcView GIS are organized in a project, which may consist of views, tables, charts, layouts, and scripts. ArcView GIS also facilities customization with its object oriented programming language called AVENUE. With AVENUE, it is possible to create a new interface and customize the existing one and automate the repetitive tasks.

The stand-alone ArcView GIS is capable of displaying, viewing, editing vector dataset called shape files. It has also the facility to display tables, charts, layouts associated with the shape files. Like ARC/INFO, ArcView GIS also consists of a number of extensions, designed to perform a particular task. The processing, modeling, visualization and interpretation of grid based raster data can be performed using the spatial analyst extension. Similarly, the three dimensional surface creation, visualization and analysis can be done using 3D analyst extension. ArcView Image Analysis facilities the advanced image integration, display, and analysis. Similarly ArcView GIS consists of a number of extensions, designed to perform special tasks. Some of these extensions are bundled with ArcView GIS and others optional ones (ArcView GIS 2007).

Working spatially

ArcView can be sued by anyone who wants to work spatially. A key feature of ArcView is that it's easy to load tabular data, such as dBASE files and from database servers, into ArcView so that any one can display, query, summarize, and organize this data geographically.

In no time will be worked with your data in a completely new way, seeing patterns could not be seen before, understanding geographic relationships that were previously hidden, gaining new insights and achieving new results for business and others.

Views

With ArcView work can be done with geographic data in interactive maps called views. Every View features ArcView's unique geographic 'Table of Content', making it easy to understand and control what's displayed.

Tables

Working with tabular data in ArcView's table puts can control. Clicking on features on a view, and their records highlight in the table their attributes will be showed. Selecting records also have a full range of feature for obtaining summary statistics, sorting and querying.

Charts

ArcView's charts offer a powerful business graphics and data visualization capability that is fully integrated into ArcViews geographic environment. Simple click on features is needed on a view to add them to the chart. ArcView lets work simultaneously with geographic, tabular and chart representations of data.

layouts

ArcView's layouts let high quality, full color maps can be created by first arranging the various graphic element on screen the way want them. You will get great looking results on a wide range of printers and plotters. layouts are smart because they have a live link to the data they represent. When print a lay out, any change to the data are automatically included, so can any one know everything on his map will be up-to-date.

Scripts

ArcView scripts are macros written in avenue, ArcView's programming language and development environment. With Avenue can be customized almost every aspect of arcView, from adding a new button to run a script is written, to create an entire custom application that can be distributed.

Projects

All the components of your ArcView session: Views, tables, charts, layouts, and scripts are conveniently stored in one file called a project. ArcView's Project window shows the contents of your projects and makes it eassy to manage all your work.

Overview of data can use in ArcView

Data that describes any part of the earth's surface or the feature found on it can be called geographic data. This includes not only cartographic and scientific data, but also business data, land records, photographs, customer database, travel guides, real estate listing, legal docoments, videos, etc.

In fact a surprisingly large amount of information is geographic. It has been found that over 80% of all the data used day-to-day in business and government can be related directly to geographic feature like zip codes, street addresses, factory location, census tracts, cities states and countries. ArcView makes it easy to work with this data geographically.

Geographic data from a variety of sources can be used in ArcView

Spatial data

Spatial data is at the heart of every ArcView application. Spatial data is geographic data that stores the geometric location of particular features, along with attribute information describing what these features represent. Also known as digital map or scanned data. For more information, see Image data and Supported image formats.

Image data

Image data includes satellite images, air photographs and other remotely sensed or scanned data. For more information, see Image data and Supported image formates.

Tabular data

Tabular data can include almost any data set, whether or not it contains geographic data. What can be done with a table in ArcView depends on what it contains. Some tables can be displayed on a view directly, others provided additional attributes that can be joined to existing spatial data. ArcView supports these formates.

Data from database servers such as Oracle, Ingres, Sybase, Informix, etc.

dBASE III files
dBASE IV files

INFO tables

Text files with fields separated by tabs or commas.

Hot linking to other data sources

Using ArcView's Hot Link Facility can be accessed virtually any other data source or application, simply by clicking on a view. For example, might be clicked on a building to display its floor plan, access a document describing it, or even play a video showing it. In this way ArcView lets organize and access diverse sources of data geographically. See Defining a hot link for a theme.

The ArcView spatial analyst tools

The ArcView Spatial Analyst is the tools for helping discover and understand spacial relationships in data. This discovery and understanding can be as simple as viewing and querying data or as complex as creating an integrated custom application. The main component of the Spatial Analyst is the grid theme. The grid is the raster equivalent of the feature theme. The Spatial Analyst also present generic spatial analysis functionality on grid and feature theme, that is added to ArcView as an extention that is loaded with Extention in the File menu when the project window is activw. The user interface components of the Spatial Analyst are loaded into the interface for views.

With the Spatial Analyst, the following functions will be able to perform on the Analyst menu:

- Find Distance
- Assign Proximity
- Calculate Density
- Cell Statistics
- Summarize Zones
- Histogram By Zone
- tabulate Areas
- Map Query

- Map Calculator
- Neighborhood Statistics
- Reclassify

The following functions are found on the surface menu:

- Interpolate Grid
- Create Contour
- Derive Slop
- Derive Aspect
- Compute Hillshade
- calculate Viewshed

The following functios are added to the Theme menu:

- Convert to Shapefile (not added, but modified to work with grid themes)
- Convert to Grid
- Save Data Set
- Edit Theme Expression

The following functions are added to the File menu:

- Manage Data Source
- Input Data Source
- Export Data Source

The following functions are added as buttons and tools:

- Histogram button

- Contour tool

Much more functionality is accessible via Avenue, such as hydrological analysis and geometric transformations, just to name a few. Search the on-line help index on 'grid' to find the Grid (Class) topic to find out all the functionality available through Avenue for the Spatial Analyst.

The ArcView 3D analyst tools

The 3D Analyst is an extension that adds support for 3D shapes,surface modeling, and real-time perspective viewing to ArcView. With it, any one can create and visualize spatial data using a third dimension to provide insight, reveal trends. and solve problems.

3D shapes

The 3D Analyst adds support for new shape types. These store z coordinates, in addition to x and y, for every point used to define a feature. The simple 3D geometry represented by these shapes has a number of uses that include:

- Storage of height information with feature geometry (in shapefiles)
- Input to surface creation process
- Output from surface analysis
- 3D visualization

Surface modeling

With the 3D Analyst installed, surface themes can be created and for analysis. Two Types of surface models are available: grid and triangular irregular networks (TINs). The power and flexibility needed to solve a wide variety of surface modeling tasks:

- Creative surface easily via ArcView's graphical interface
- Modify existing TIN based surface
- Perform a variety of tasks including contouring, profiling, color hillshade mapping, and more

- Real-time perspective Viewing

The 3D Analyst adds a new document type to the ArcView interface; the 3D Scene Document. This document provides an interactive viewer that puts your data in a new perspective.

- View and validate 3D data in perspective.
- See your 2D features in 3D by draping and extruding.
- navigate and move around in real-time.
- Gain New insights.

The ArcView conversion tools

The Conversion toolset provides a wide range of tools for converting various data types, including 3D features, rasters, terrains, TINs, and LAS datasets. TIN surfaces can be imported from LandXML files, 3D features can be exported to ASCII files, and lidar data can be imported to a multipoint dataset. Converting between raster and TIN formats allows to employ the benefits of each while modeling the same surface. For example, use a TIN to model a surface if features have , such as lines or polygons, that should enforce natural features, such as ridges or valleys. Convert the TIN to a raster using the natural neighbors interpolation option to preserve the linear features and use spatial operators.

The ArcView data management tools

The Data Management toolset provides a collection of tools for creating, managing, and editing terrain, TIN, and LAS (lidar and surface) datasets that are organized under the following toolsets:

- **LAS Dataset:** Contains tools for modifying classification of LAS files referenced by a LAS dataset, which is a new data type that allows for the rapid read and display of airborne lidar data.
- **Terrain Dataset:** Contains tools for creating and managing a terrain dataset, which is a multiresolution triangulated surface comprised of feature based measurements stored in a feature dataset.

- **TIN:** Contains tools for creating and editing a triangulated irregular network (TIN) dataset, which is a single resolution surface comprised of feature based measurements.

3.3 HEC-RAS

Introduction

HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. The HEC-RAS system will ultimately contain three one-dimensional hydraulic analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; and (3) movable boundary sediment transport computations. A key element is that all three components will use a common geometric data representation and common geometric and hydraulic computations routines. In addition to the three hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed (HEC-RAS 2010).

Overview of program capabilities

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.

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

River 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/expansion (coefficient multiplied by the change in velocity head). 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 and/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. However, with the release of Version 3.1, the model can now perform mixed flow regime (subcritical, supercritical, hydraulic jumps, and draw downs) calculations in the unsteady flow computations module.

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.

Sediment transport/Movable boundary computations

This component of the modeling system is intended for the simulation of one-dimensional sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods (typically years, although applications to single flood events are possible).

The sediment transport potential is computed by grain size fraction, thereby allowing the simulation of hydraulic sorting and armoring. Major features include the ability to model a full network of streams, channel dredging, various levee and encroachment alternatives, and the use of several different equations for the computation of sediment transport.

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

Water quality analysis

This component of the modeling system is intended to allow the user to perform riverine water quality analyses. The current version of HEC-RAS can perform detailed temperature analysis and transport of a limited number of water quality constituents (Algae, Dissolved Oxygen, Carbonaceuos Biological Oxygen Demand, Dissolved Orthophosphate, Dissolved Organic Phosphorus, Dissolved Ammonium Nitrate, Dissolved Nitrite Nitrogen, Dissolved Nitrate Nitrogen, and Dissolved Organic Nitrogen). Future versions of the software will include the ability to perform the transport of several additional water quality constituents.

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 filename is entered, all other files are automatically created and named by the interface as needed. The interface provides for renaming, moving, and deletion of files on a project-by-project basis.

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 pre-defined tables or develop their own customized tables. All graphical and tabular output can be displayed on the screen, sent directly to a printer (or plotter), or passed through the Windows Clipboard to other software, such as a word-processor or spreadsheet.

Reporting facilities allow for printed output of input data as well as output data. Reports can be customized as to the amount and type of information desired.

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 a 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

3.4 Theoretical basis for 1D flow calculations (HEC-RAS)

In steady-state modeling, the flows are prescribed by the user and the model calculates water levels at discrete cross-sections. There is essentially one unknown variable (stage) and therefore, one equation is needed - the energy equation. In unsteady modeling, two variables are calculated (stage and flow), so two equations are needed. Unsteady modeling is also, concerned with how these parameters change with time and distance downstream. This is reflected in the partial differential terms in the equations.

3.4.1 Steady Flow Water Surface Profiles

Different fundamental equations used for HEC-RAS algorithm to compute water surface elevations using the standard step method for steady flow analysis are:

Energy equations

Water surface profiles are computed from one cross-section to the next by solving the Energy Equation with an iterative procedure. Energy equation is based on Principle of conservation of the energy and it states that the sum of the kinetic energy and potential energy at a particular cross-section is equal to the sum of the potential and kinetic energy at any other cross section plus or minus energy loss or gains between the sections. The energy equation can be written as follows (HEC-RAS 2010):

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \tag{3.1}$$

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 3.1.

The energy head loss (h_e) is expressed as

$$h_e = LS_f + C\left|\frac{\alpha_2^2 V_2^2}{2g} - \frac{\alpha_1^2 V_1^2}{2g}\right| \tag{3.2}$$

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:

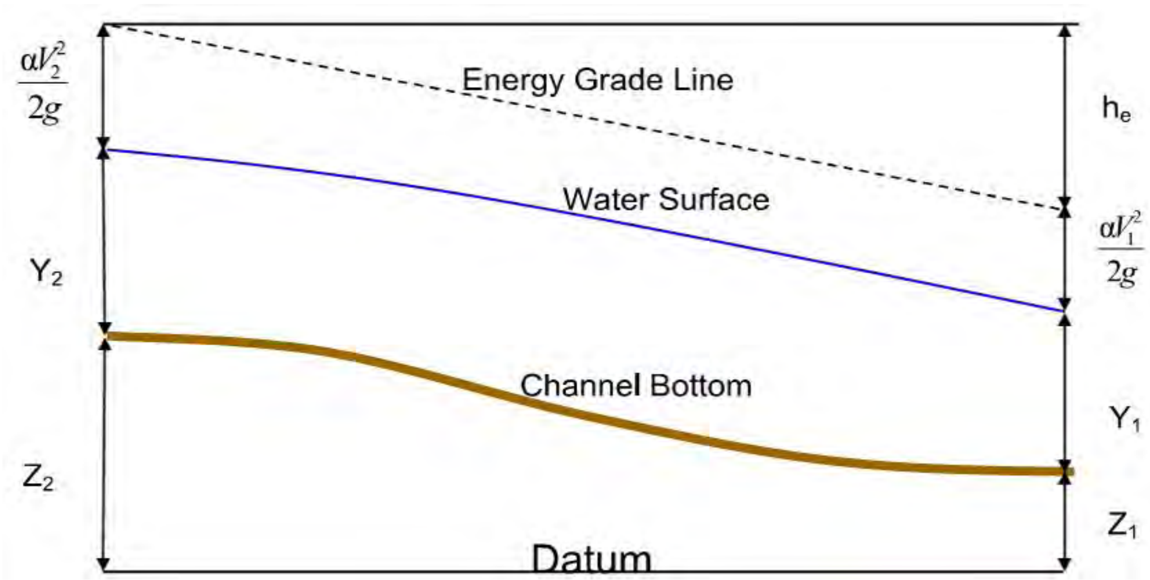


Figure 3.1: Representation of terms in the energy equation

$$L = \frac{L_{lob}Q_{lob} + L_{CH}Q_{Ch} + L_{rob}Q_{rob}}{Q_{lob} + Q_{ch} + Q_{rob}} \tag{3.3}$$

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

Calculation of conveyance

The determination of total conveyance and the velocity coefficient for a cross-section requires that flow be sub-divided into units for which the velocity is uniformly distributed. The approach used in HEC-RAS is to sub-divide flow in the overbank areas using the input cross-section n-value break points (location where n-values change) as the basis for sub-division. Conveyance is calculated within each sub-division forms the following form of Manning's equation:

$$Q = KS^{\frac{1}{2}}f \tag{3.4}$$

$$K = \frac{1}{n}AR^{\frac{2}{3}} \tag{3.5}$$

Where: K = conveyance for sub-division

n = Manning's roughness coefficient for sub-division

A = flow area for sub-division

R = hydraulic radius for sub-division

All the incremental conveyances in the overbank are summed to obtain a conveyance

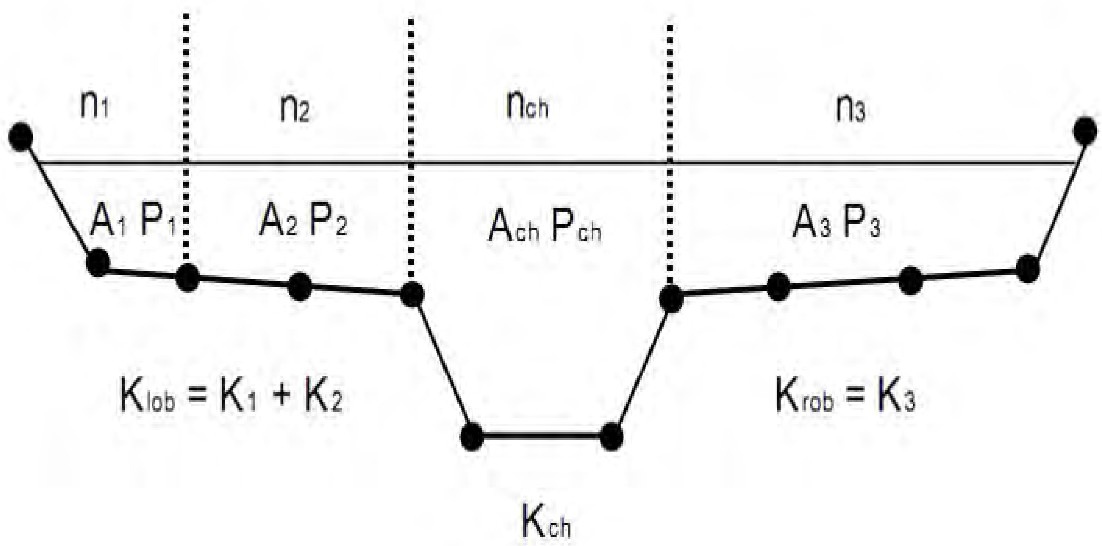


Figure 3.2: HEC-RAS default conveyance subdivision method

for the left and the right overbank and the total conveyance for the cross-section is obtained by summing the three subdivision conveyances (left, channel and right) figure 3.2.

Calculation of mean kinetic energy head

Mean kinetic energy head for each cross-section is obtained by computing the flow weighted kinetic energy heads for three sub-sections of the cross-sections (Left Overbank, Channel, and Right Overbank). 2.3 illustrates the mean kinetic energy calculation process for a cross-section with a main channel and right overbank.

To compute the mean kinetic energy it is necessary to obtain the velocity head

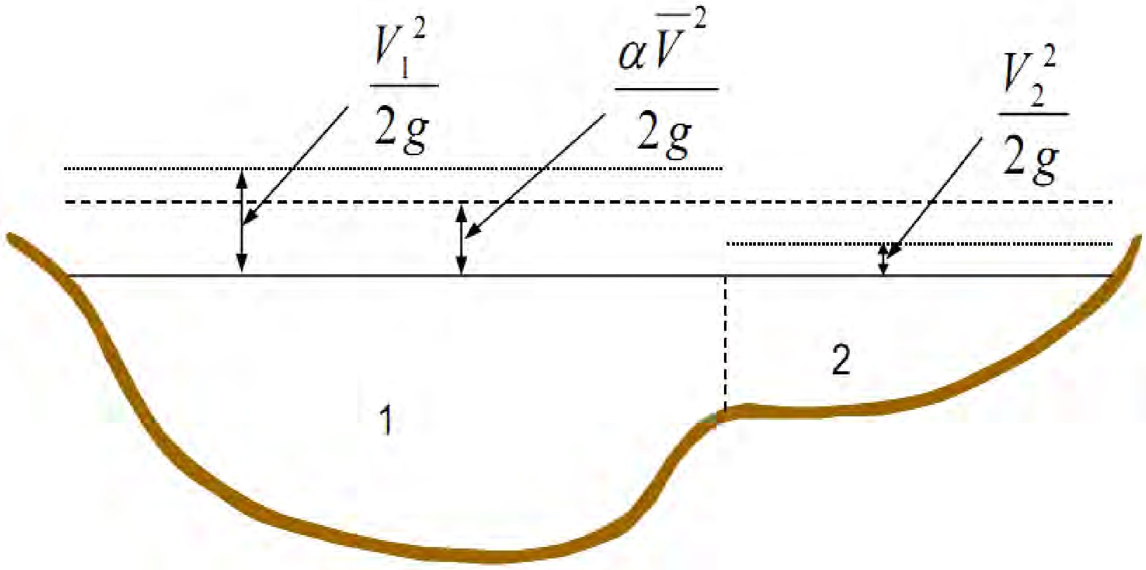


Figure 3.3: Example of how mean energy is obtained

weighting coefficient alpha. Alpha can be calculated by using following equation.

$$\alpha = (A_t)^2[K_{lob}^3/A_{lob}^2 + K_{ch}^3/A_{ch}^2 + K_{rob}^3/A_{rob}^2]/K^3t \tag{3.6}$$

Where: A_t = total flow area of cross-section

A_{lob}, A_{ch}, A_{rob} = flow areas of left overbank, main channel right overbank respectively

K_t = total conveyance of cross-section

K_{lob}, K_{ch}, K_{rob} = conveyance of left overbank, main channel and right over bank, respectively

Saint-Venant equations

Unsteady, gradually varied flow simulation model i.e. HEC-RAS, which is dependent on finite difference solutions of the Saint-Venant equations (Equations (3.7)-(3.8)), has been used to simulate the flood in the Jamuna River.

$$\frac{\partial u}{\partial t} = \frac{\partial Q}{\partial t} \tag{3.7}$$

$$\frac{\partial Q}{\partial t} = \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gA(S_0 - S_f) \tag{3.8}$$

Here A = cross-sectional area normal to the flow; Q =discharge; g = acceleration due to gravity; H = elevation of the water surface above a specified datum, also called stage; S_0 = bed slope; S_f = energy slope; t = temporal coordinate and x = longitudinal coordinate. Equations (3.7) and (3.8) are solved using the well known four-point implicit box finite difference scheme (HEC-RAS 2010). This numerical scheme has been shown to be completely non dissipative but marginally stable when run in a semi-implicit form, which corresponds to weighting factor (θ) of 0.6 for the unsteady flow simulation. In HEC-RAS, a default is1, however, it allows the users to specify any value between 0.6 to 1. The box finite difference scheme is limited to its ability to handle transitions between subcritical and supercritical flow, since a different solution algorithm is required for different flow conditions. The said limitation is overcome in HEC-RAS by employing a mixed-flow routine to patch solution in sub reaches.

3.5 HEC-GeoRAS

Introduction

HEC-GeoRAS is an ArcView GIS extension specifically designed to process geo-spatial data for use with the Hydrologic Engineering Center River's Analysis System (HEC-RAS). The extension allows users to create an HEC-RAS import file containing geometric attribute data form an existing digital terrain model (DTM) and complementary data sets. Water surface profile results may also be processed to visualize inundation depths and boundaries. HEC-GeoRAS extension for ArcView GIS used an interface method to provide a direct link to transfer information between the ArcView GIS and the HEC-RAS (HEC-GeoRAS 2009).

Overview of requirements

HEC-GeoRAS 4.2 is an extension fo ruse with ArcGIS(Environmental Systems Research Institute,2000) that provides the user with a set of procedures,tools, and utilities for the preparation of GIS data for import in to RAS and generation of GIS data from

RAS output. While the GeoRAS tools are designed for users with limited geographic information systems(GIS) experience,extensive knowledge of ArcGIS is advantageous. Users, however, must have experience modeling with HEC-RAS and havea thorough understanding of river hydraulics to properly create and interpret GIS data sets.

Software requirements

HEC-GeoRAS 4.2 is for use with ArcGIS 9.3. Both the 3D Analyst extension and the Spatial Analyst extension are required.

The full functionality of HEC-GeoRAS 4.2 requires HEC-RAS 4.0, or later , to import and export all of the GIS data options. Older versions of HEC-RAS may be used, how ever , with limitations on importing roughness coefficients, ineffective flow data, blocked obstruct ions, levee data, hydraulic structures, and st or age area data. Further , data exported from older versions of HEC-RAS should be converted to the lat est XML file structure using t he SDF to XML conversion tools provided.

Data requirements

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

Getting started

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

When the HEC-GeoRAS extension loads, menus and tools are automatically added to the ArcMap interface. Menus are denoted by text and tools appear as buttons. These menus and tools are intended exported HEC-RAS simulation results. The HEC-

GeoRAS tool bar is shown in Figure 3- 2. to aid the user in stepping through the geometric data development process and post-processing of exported HEC-RAS simulation results.The HEC-GeoRAS tool bar is shown in Figure 3.4.

Figure 3.4: HEC-GeoRAS toolbar

HEC-GeoRAS menus

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

RAS geometry

The RAS Geometry menu is for pre-processing geometric data for import into HEC-RAS. Items are listed in the RAS Geometry dropdown menu in the recommended (and sometimes required) order of completion. Items available from the RAS Geometry menu items are shown in Figure 3.5

Figure 3.5: HEC-GeoRAS geometry processing menu items.

RAS mapping

The RAS Mapping menu is for post-processing exported HEC-RAS results. Items available from the RAS Mapping dropdown menu are listed in the required order of complete RAS Mapping menu are shown in Figure 3.6.

Figure 3.6: HEC-GeoRAS mapping menu items.

ApUtilites

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

You MUST add new Data Frames (Maps) using the ApUtilites. Add New Map menu item. Otherwise GeoRAS will not find the proper data sets to work with!

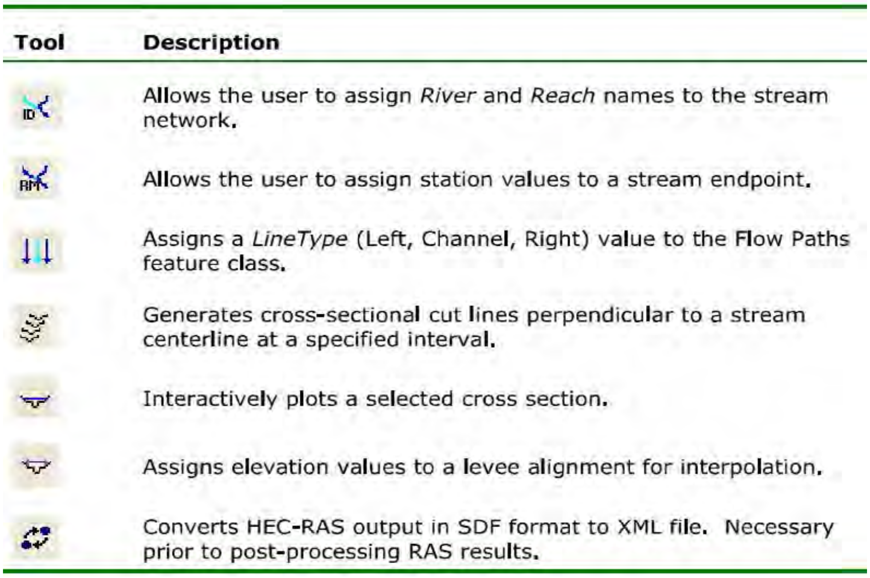
Help

The Help menu will provide general online help information and version is consistent with the ArcGIS product it is being used with provide the version number. Use the

"About HEC-GeoRAS" menu item to verify the version is consistent with the ArcGIS product it is being used with!

HEC-GeoRAS tools

There are several tools are provided in the toolbar. A tool waits for user action after being activated and will either invoke a dialog or change the mouse pointer, indicating the need for further action. Figure 3.7 show the Summary of HEC-GeoRAS tools.



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

Figure 3.7: Summary of HEC-GeoRAS tools.

Chapter 4

Methodology

4.1 Data collection

Distinct sets of data were collected from different organizations for this study. Among the collected data, geometric data like bathymetry of the river, hydrologic data like discharge, water level, flood inundation map and digital elevation model as land topographic data were included. All collected data are summarized in the table : 4.1. A brief description of all the data used in the study are presented in the following.

Table 4.1: Collected data list

Data Type	Source	Data location	Periods
Bathymetric data	IWM	Jamuna River	2011
Discharge data	BWDB	Bahadurabad station	1956 - 2012
Water level	BWDB	Sirajganj station	2001 - 2007
Water level	BWDB	Kazipur station	2004 - 2005
Water level	BWDB	Mathurapara station	2004 - 2005
DEM	NASA	Bangladesh	2014
Flood map	FFWC	Bangladesh	2004 and 2007
Rainfall	BMD	Bogra	1950 - 2013

4.1.1 Bathymetric data

A representation of the 3D nature of the subaqueous land surface is called bathymetry. The bathymetric data of 2011 of the Jamuna River were collected from the Institute of Water Modelling (IWM). A contour of the bathymetric data is shown in figure: 4.1.

4.1.2 Hydrologic data

Discharge data

The flood hydrograph of the Jamuna River at Bahadurabad gauge station was collected from the Bangladesh Water Development Board (BWDB), which has been used as the upstream boundary condition. The data of year 2004 have been used to calibrate and of year 2005 have been used to validate the hydrodynamic model. The hydrograph comprises of data at an interval of one day. The historical yearly maximum discharge data of years from 1957 to 2012 were also collected for flood frequency analysis. The detailed discharge data are shown in Appendix-A.

Water level data

The stage hydrograph of the Jamuna River at the Sirajganj gauge station was collected from the Bangladesh Water Development Board (BWDB), which has been used as the downstream boundary condition. Kazipur and Mathurpara gauge station data were also collected for calibration and validation. The data of year 2004 have been used to calibrate and of year 2005 have been used to validate the hydrodynamic model. The hydrograph comprises of data at an interval of one day. The detailed water level data are shown in Appendix-A.

4.1.3 Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) of Bangladesh was obtained from the FTP server of the Shuttle Radar Topographic Mission (SRTM) of National Aeronautics and Space Administration (NASA) (http://www.cgiar-csi.org/). The data comprises of a resolution of 90m x 90m. The elevation of the DEM has been measured with respect to the mean sea level. All the data in the DEM have been projected on to the Bangladesh Transverse Mercator (BTM).

4.1.4 Flood map

The historical flood map of Bangladesh in the year of 2004 and 2007 ware collected from Flood Forecasting and Warning Center (FFWC). These 2004 and 2007 flood map have been shown in Appendix-B.

4.1.5 Meteorological data

Monthly average rainfall data of Bogra gauge station from 1950 to 2013 have been collected from Bangladesh Meteorological Department (BMD). The Rainfall data are used for analyzing the rainfall pattern of the Jamuna River basin.

4.2 Frequency analysis

The flood frequency analysis is one of the important studies of river hydrology. It is essential to interpret the past record of flood events in order to evaluate future possibilities of such occurrences. The estimation of the frequencies of flood is essential for the quantitative assessment of the flood problem.

Frequency of a hydrologic event, such as the annual peak flow is the probability that a value will be equaled or exceeded in any year. The length of record should be sufficient to justify extrapolating the frequency relationship. For example, it might be reasonable to estimate a 50-year flood on the basis of a 30-year record, but to estimate a 100-year flood on the basis of a 10-year record would normally be absurd (BWDB 2010). Frequency analysis is cautioned when working with shorter records and estimating frequencies of hydrologic events greater than twice the record length (Viessman and Lewis 1996). The flood frequency analysis is one of the important studies of river hydrology which was conducted based on maximum instantaneous flow (Yadav 2002)

Frequency analysis can be conducted in two ways: one is the analytical approach and the other is the graphical technique in which flood magnitudes are usually plotted against probability of exceedance. Different frequency analysis method are described the following section.

4.2.1 The Gumbel's method

The Gumbels method (Gumbel Distribution) is the most widely used probability distribution function for extreme values in hydrologic and meteorological studies for prediction of flood peaks and maximum rainfalls (Chow *et al.* 1988). In this method the variate X (maximum rainfall or flood peak discharge) with a recurrence interval T is given by

$$X_T = u + \alpha y_T \tag{4.1}$$

Where X_T= is a flood of specified probability or return period T ;

u=$X_{avg} - 0.5772\alpha$;

X_{avg}= is the mean of the flood series ;

$\alpha = \frac{\sqrt{6}}{\pi} S$;

S= Standard deviation of sample size ;

N=$\sqrt{\frac{\sum(x-x_{avg})^2}{N-1}}$;

y_T=$-ln[ln(\frac{T}{T-1})]$;

4.2.2 Normal distribution

Chow *et al.* (1988) has shown that most frequency functions can be generalized to

$$X_T = X_{avg} + K_T S_y \tag{4.2}$$

Where X_T= is a flood of specified probability or return period T ;

X_{avg}= is the mean of the flood series ;

S_y= is the standard deviation of the series ;

$K_T = \frac{x_T - x_{avg}}{S_y} = Z_T$;

Where for flood flow $Z_T = \frac{(1-\frac{1}{T})^{0.135} - \frac{1}{T}^{0.135}}{0.1975}$;

And for low flow $Z_T = \frac{\frac{1}{T}^{0.135} - (1-\frac{1}{T})^{0.135}}{0.1975}$;

4.2.3 Log Normal distribution

If a random variable x has a log normal distribution (LN2) then the log transformed variable has a normal distribution. The transformed variable is denoted by

$$y = lnx \tag{4.3}$$

$Where, X > 0$. The maximum likelihood method is generally best for fitting the LN2 distribution. The maximum likelihood method gives:

$$y_{avg} = \frac{\sum_{i=1}^{n} ln(X_i)}{n} \; ;$$

$$S_y = \frac{\sum_{i=1}^{n} [ln(X_i) - y_{avg}]}{n} \; ;$$

Estimate of flood flow corresponding to T-year return period can be obtained from
$X_T = antilog(y_{avg} + Z_T S_y)$;

Where for flood flow $Z_T = \frac{(1-\frac{1}{T})^{0.135} - \frac{1}{T}^{0.135}}{0.1975}$;

And for low flow $Z_T = \frac{\frac{1}{T}^{0.135} - (1-\frac{1}{T})^{0.135}}{0.1975}$;

4.2.4 Pearson Type III distribution

The Pearson Type III Distribution (P3) has three parameters. A P3 distribution can be fitted to a sample of data by using the product moment of the data.
Estimate of flood flow corresponding to T-year return period can be obtained from

$$X_T = X_{avg} + K_T S_x \tag{4.4}$$

Where K_T is a frequency factor. The frequency factor for $T < 100$ years and absolute value of skewness < 2 are well approximate by the Wilson-Hilferty transformation.
$K_T = \frac{2}{g_x(1+(Z_T \frac{g_x}{6}) - \frac{g_x^2}{36})^3} - \frac{2}{g_x}$;

Where Z_T is the standard normal variate and S_x, g_x are standard deviation and coefficient of skewness of normal data (not transformed) respectively.

4.2.5 Log Pearson Type III distribution

Log Pearson Type III Distribution (LP3) describes a random variable whose logarithms are P3 distributed. Thus

$y = lnx$;

the method of estimating the parameters of the LP3 distribution is similar to that for the P3 distribution except that logarithms of the data are to be taken before estimating moments. Thus for a set of observations $x_1, x_2, ...x_n$ the transformed data are given by $y_1 = lnx_1$. $y_2 = lnx_2........, y_n = lnx_n$. Estimate of flood flow corresponding to T-year return period can be obtained from

$$X_T = antilog(y_{avg} + K_T S_s) \ ;$$

$$K_T = \frac{2}{g_x(1+(Z_T\frac{g_x}{6})-\frac{g_x^2}{36})^3} - \frac{2}{g_x} \ ;$$

Where g_y is the coefficient of skewness of log transformed data.

Frequency analysis is merely a procedure for estimating the frequency of occurrence or probability of occurrence of past or future events. To determine the discharge of Bahadurabad in response to 2, 5, 10, 25, 50 and 100-year return periods flood frequency analysis has been conducted based on the discharge data for the year 1956 to 2006. To select the appropriate distribution a total of five distributions has been compared in this study. These are Normal Distribution, Log Normal Distribution, Pearson Type III Distribution, Log Pearson Type III Distribution and Gumble Distribution. The comparison is based upon goodness-of-fit analysis. Based on 2, 5, 10, 25, 50 and 100-year return periods, discharge has been used in HEC-RAS model to generate flood water surface profile for flood inundation map. The detailed calculation of frequency analysis has been shown in appendix-C.

4.2.6 Goodness-of-fit analysis

Probability plot correlation coefficient (PPCC)

Goodness - of - fit study based upon the probability plot correlation coefficient (PPCC) is useful for assessing whether a proposed distribution is consistent with the at-site data sample (Stedinger *et al.* 1993). Another goodness-of-fit analysis based upon probability plot (plotting position) is the root mean square deviation (RMSD) in fit. Goodness-of-fit analysis based upon PPCC is employed in this study.

The adequacy of a fitted distribution can be evaluated by the PPCC which is essentially a measure of the linearity of probability plot. It gives the correlation between the ordered observations and the corresponding fitted quantiles determined by a plotting position. If Y denotes the observed i-th flow, W the computed flow at the i-th plotting position, Y_{avg} the average value of observations and W_{avg} the average value of computed flows, then the PPCC of the fitted distribution for n sample size at a site is given by

$$\rho = \frac{\sum_{i=1}^{n}(Y_i - Y_{avg})(W_i - W_{avg})}{\sqrt{\sum_{i=1}^{n}(Y_i - Y_{avg})^2(W_i - W_{avg})^2}} \tag{4.5}$$

The maximum value of PPCC can be equal to one. Among fitted distributions to a sample of data, the one with the largest PPCC has the best fit to the data. For selection of the best fitted method of flood frequency analysis for Bahadurabad station, the above procedure has been used. The detail calculation of PPCC are shown in appendix-C.

Chi-Square Test

The goodness of fit of a probability distribution can be tested by comparing the theoretical and sample values of the relative frequency. In the case of the relative frequency function, the Chi-Square test is used.
The test statistic is given by:

$$X^2 = \sum_{i=1}^{k} \frac{n[f_s(x_i) - p(x_i)]^2}{p(x_i)} \tag{4.6}$$

where k is the number of intervals; the sample value of the relative frequency of interval i is, $f_s(x_i) = n_i$/n; the theoretical value of the relative frequency function (also called incremental probability function) is $p(x_i) = F(x_i) - F(x_{i-1})$.

4.3 Bathymetric grid creation

The river bathymetric data collected from Institute of Water Modelling (IWM) has been used for the generation of the shape file. Data Management tool of ArcGIS has been used to create shape file.

To create a surface grid in ArcGIS, the 'Spatial Analyst' extension employs one of several interpolation tools. Interpolation is a procedure used to predict the values of cells at locations that lack sampled points. It is based on the principle of spatial autocorrelation or spatial dependence, which measures degree of relationship/dependence between near and distant objects. ArcGIS Spatial Analyst at version 9.3 offers several interpolation tools for generating surface grids from point data. The 'Topo to Raster' command has been added to the IDW, Spline and Kriging interpolation methods that were available in 'Spatial Analyst' of ArcGIS 9.3. Each method uses a different approach for determining the output cell values. The most appropriate method will depend on the distribution of sample points and the phenomenon being studied. Among these tools, Kriging is a powerful statistical interpolation method which is used for diverse applications such as health science, geochemistry and pollution modeling (Childs 2004). Kriging assumes that the distance or direction between sample points reflects a special correlation that can be used to explain variation in the surface. It fits a function to a special number of points or all points within a specified radius to determine the output value for each location. Kriging is the most appropriate when a spatially correlated distance or directional bias in the data is known and is often used for application of soil science and geology. The predicted values are derived from the measure of relationship in sample using sophisticated weighted average technique. It uses a search radius that can be fixed or a variable. There are several types of Kriging. Ordinary Kriging, the most common method, assumes that there is no constant mean for the data over a mean area. Universal Kriging assume that an overriding trend exists in the data and that it can be modeled.

In this study, Kriging interpolation method has been used to create the surface grid of the river bathymetry. The size of the grids has been chosen as 10 meter. The created topographic grid contains some default topographic data that are not appropriate. Only river bathymetric grid is needed. Extraction of grid needs the 'Grid Analyst' extension. A polygon has been drawn in accordance with the river bathymetric size. Using this polygon the bathymetric grid file has been extracted from the topographic grid file. In this operation 'Extracted Grid from this Polygon' tool from 'Grid Analyst' menu has been used. The bed level for bathymetry was referenced with respect to the Public Works Datum (PWD) of Bangladesh, which is established by the Department of Public Works, Bangladesh. The complete bathymetric grid has been shown in figure 4.1.

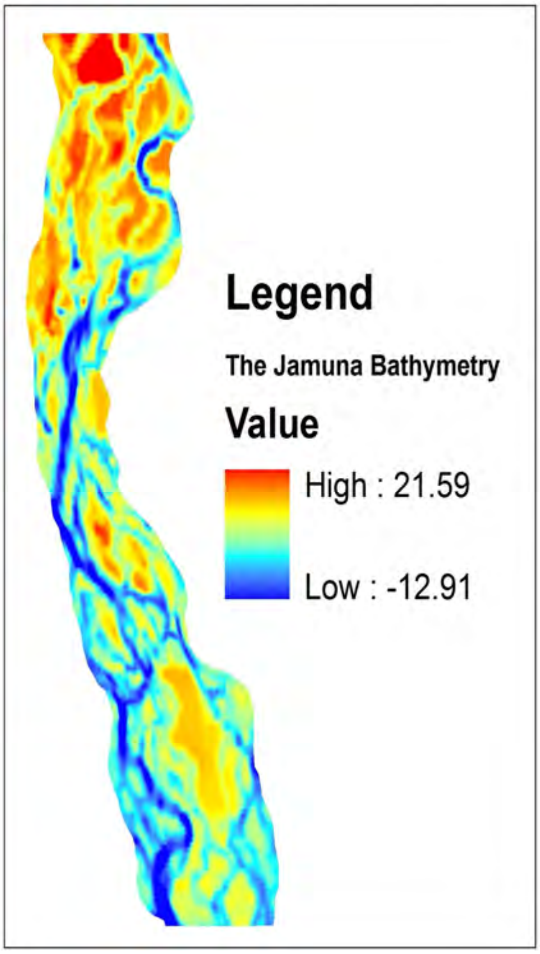


Figure 4.1: The river bathymetric grid

4.4 DEM processing

DEMs are increasingly used for visual and mathematical analysis of topography, landscapes and landforms, as well as modelling of surface processes. The accuracy of a DEM is determined by data type and actual sampling technique of the surface during DEM creation. A DEM offers the most common way of showing topographic information and even enables the modeling of flow across topography, a controlling factor in distributed models of land form processes (Miliaresis and Argialas 2000). In this research, Digital Elevation Model (DEM) has been obtained from the Shuttle Radar Topographic Mission (SRTM) (http://www.cgiar-csi.org/).

4.4.1 DEM re-sampling

The SRTM 90m DEM has a resolution of 90 m at the equator, and are provided in mosaicked 5 deg x 5 deg tiles. There are four tiles covering Bangladesh. After downloading the DEM, the study area DEM has been clipped from the entire DEM by using the data management tool. Finally, DEM has been resampled into 10*10m resolution. The elevation of the DEM has been measured relative to the mean sea level (MSL). The PWD datum is 0.46 m above the Mean Sea Level (MSL) datum. DEM's value has been transferred to PWD datum by adding 0.46 m . All the data in the DEM have been projected on to the Bangladesh Transverse Mercator (BTM). The complete digital elevation model has been shown in figure 4.2.

4.4.2 Merging bathymetric grid with DEM

The topographic DEM doesn't contain the bathymetric of the river. The extracted grid contains the bathymetric grid but not topographic grid. So the bathymetric grid has been merged with the topographic DEM to produce the complete DEM of the river bathymetry along with the topographic DEM. Merging complete DEM has been shown in figure 4.3.

The approach used for floodplain analysis and hazard assessment using one-dimensional model using HEC-RAS, GIS and HEC-GeoRAS are shown in 4.4.

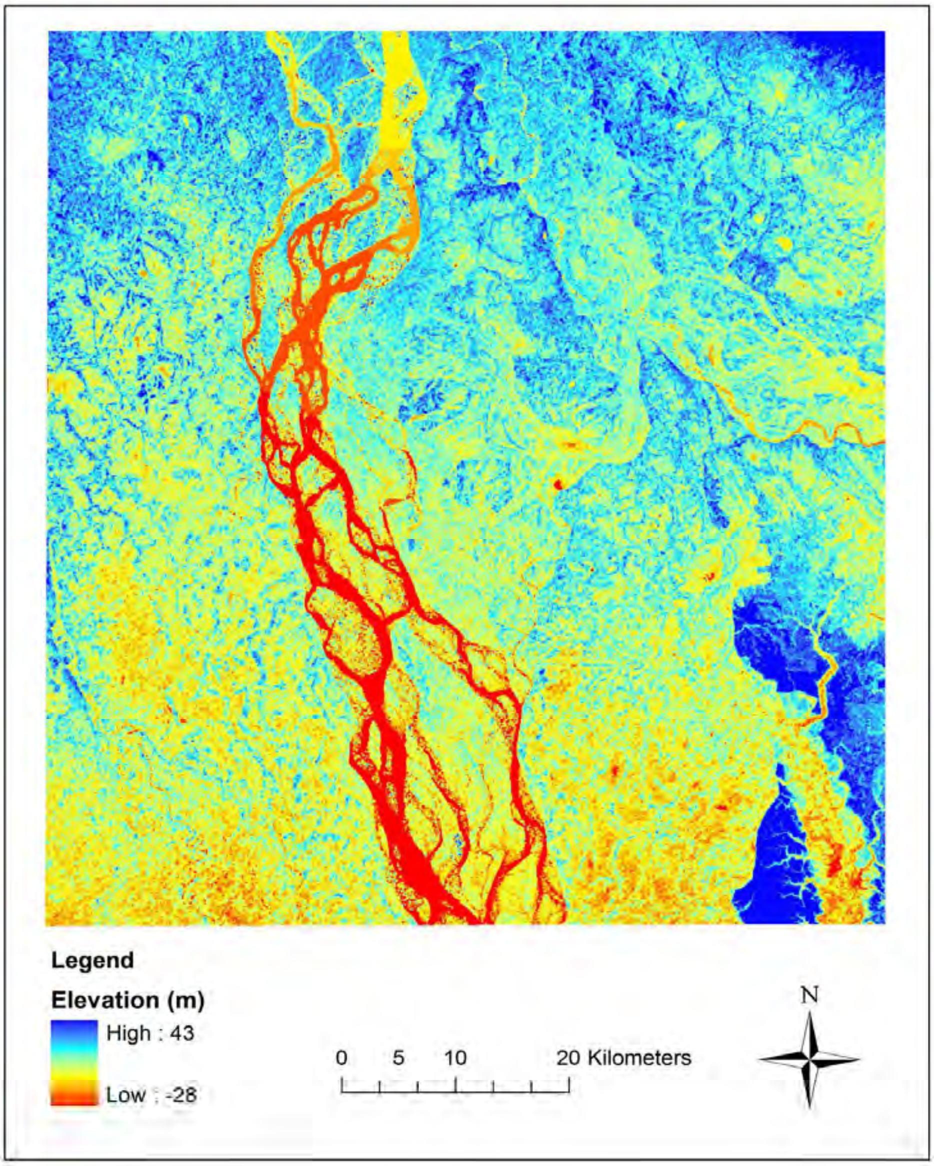


Figure 4.2: DEM of study area

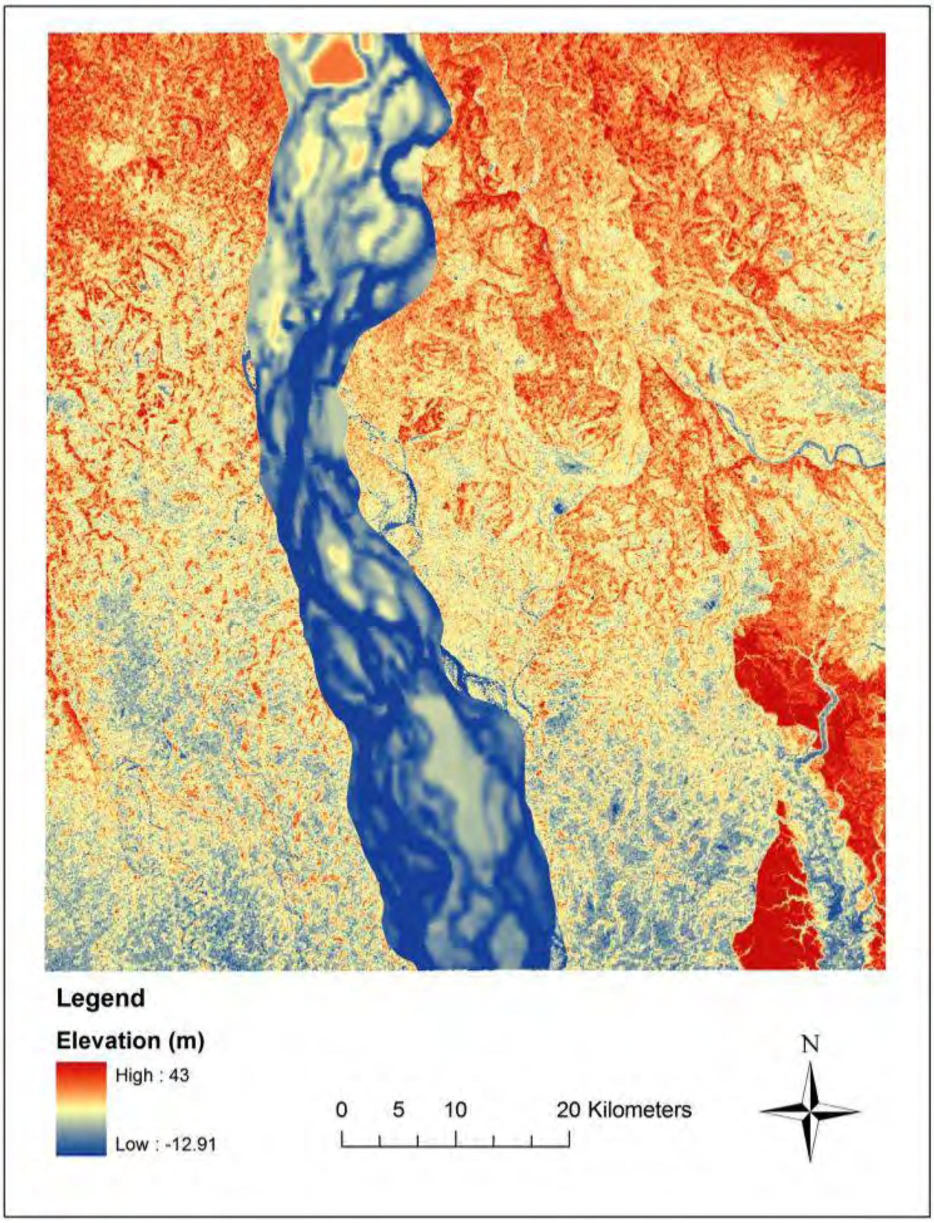


Figure 4.3: DEM with bathymetry

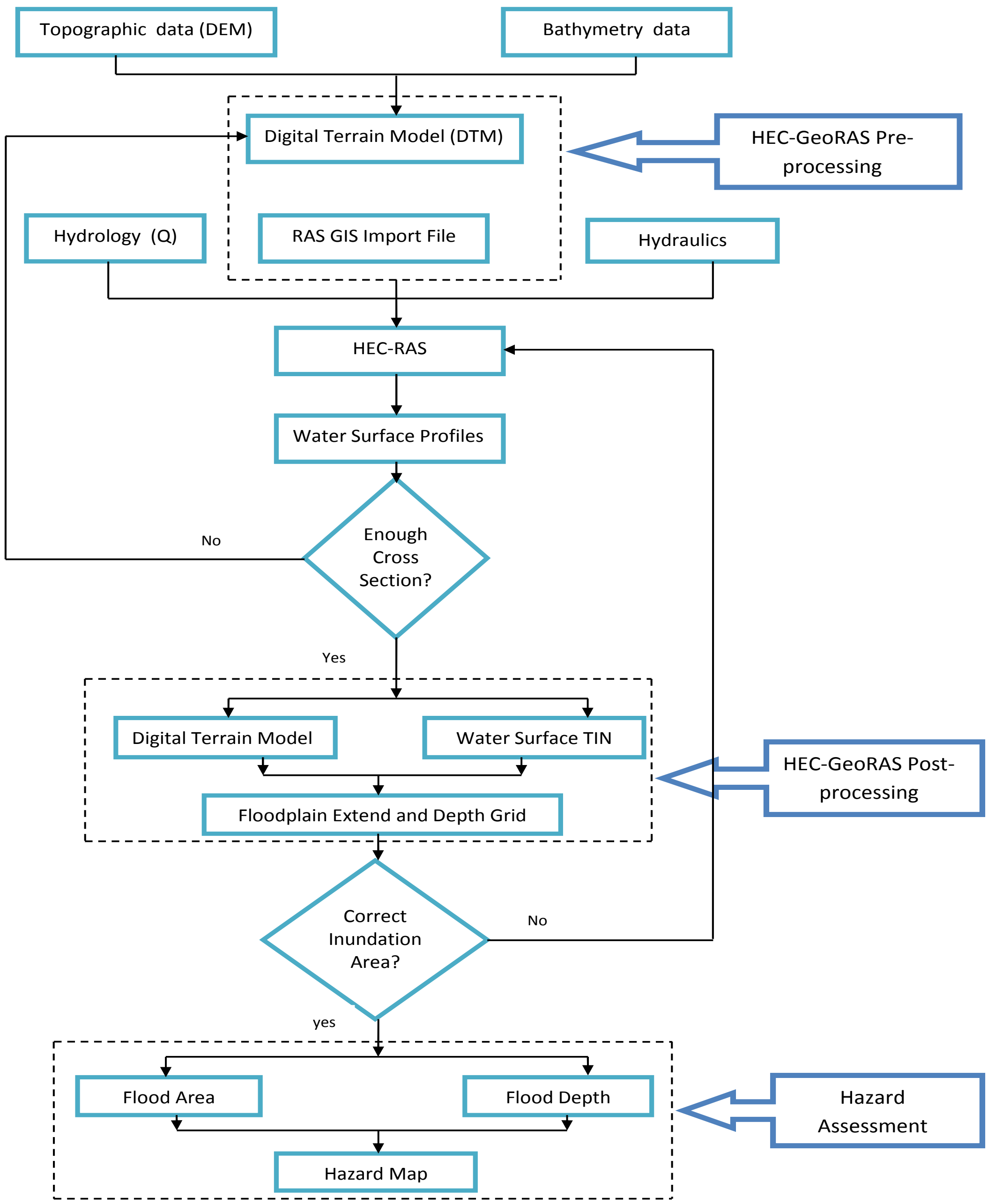


Figure 4.4: One dimensional floodplain analysis using HEC-RAS, GIS and HEC-GeoRAS

4.5 HEC-GeoRAS based study

HEC-GeoRAS is an ArcView GIS extension specifically designed to process geo-spatial data to incorporate with the Hydrologic Engineering Center River's Analysis System (HEC-RAS). The extension allows users to create an HEC-RAS import file containing geometric attribute data form an existing digital terrain model (DTM) and complementary data sets. Water surface profile results may also be processed to visualize inundation depths and boundaries. HEC-GeoRAS extension for ArcView GIS used an interface method to provide a direct link to transfer information between the ArcView GIS and the HEC-RAS as shown in figure 4.5 . HEC-GeoRAS is organized as pre-processing (preRAS) and post-processing (postRAS) facilitated by menu and buttons.

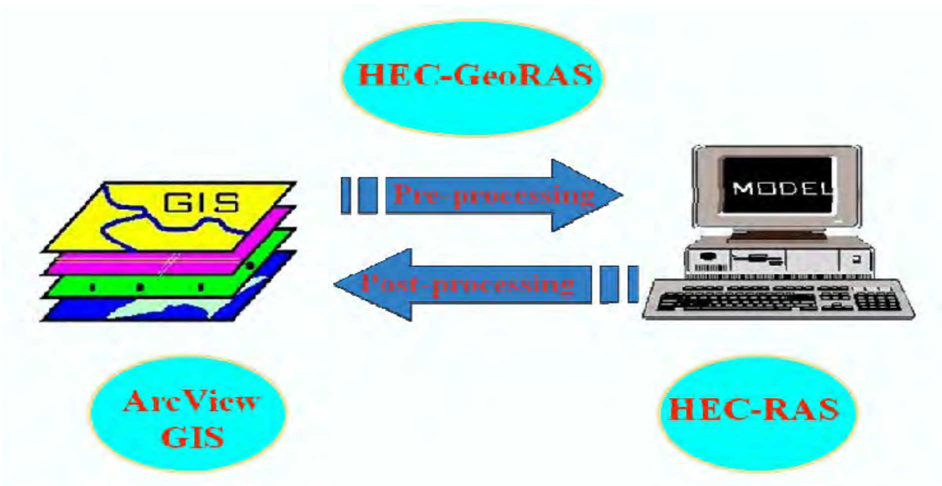


Figure 4.5: Interface method of GIS linkage by HEC-GeoRAS

4.5.1 Pre-processing to develop the RAS GIS import file

The complete GRID has been created by the merging topographic DEM with bathymetric grid . Now the geometric data of the river bathymetry along with the topography can be extracted from the GRID. The goal of this section is to develop the spatial data required to generate a HEC-RAS import file with a 3-D river network and defined 3-D cross sections. This extraction comprises several steps. These are development of a river centerline, cross-sections, river banks, and flowpath lines as shape files.

River centerline creation

At first, GRID has been chosen as a DTM layer. The created river centerline command from the preRAS menu has been selected. Name the new shape file as **Jamuna.shp**. The file will be automatically in the edit mode. Highlighting the **Jamuna.shp** theme in the legend, click on the start editing command under the theme menu. With the pencil has been chosen begin to digitize in the centerline, following the deepest part of the channel. The digitize has been done from the upstream to the downstream of the river. When the digitize has been finished, right click and choose finish sketch. Attribute table has been opened to give "HydroID" of the river which is a unique identifier for each river. River centerline is shown in figure 4.6.

River banks creation

The river banks separate the main channel from the overbank areas when flooding occurs. It differentiates the resistance of the main channel and the overbanks. This is important for a steady-state simulation.

To create the river banks layer, "Bank Lines" option has been clicked under "Create RAS Layers" menu. The theme appeared in the legend in the edit mode. Before beginning to create the banks theme, the following rules to remember to digitizing:

Rules:

- Have exactly two bank lines per cross section. Make sure to have a left and right bank defined, but no more than that.
- Bank lines may be broken. The theme does not have to be a continuous polyline along a side of the channel.
- Orientation of the banks lines is unimportant.Start on the left or right of the stream centerline, as well as upstream or downstream. It does not matter.
- Creating this theme is optional when using GeoRAS. For this exercise, we will

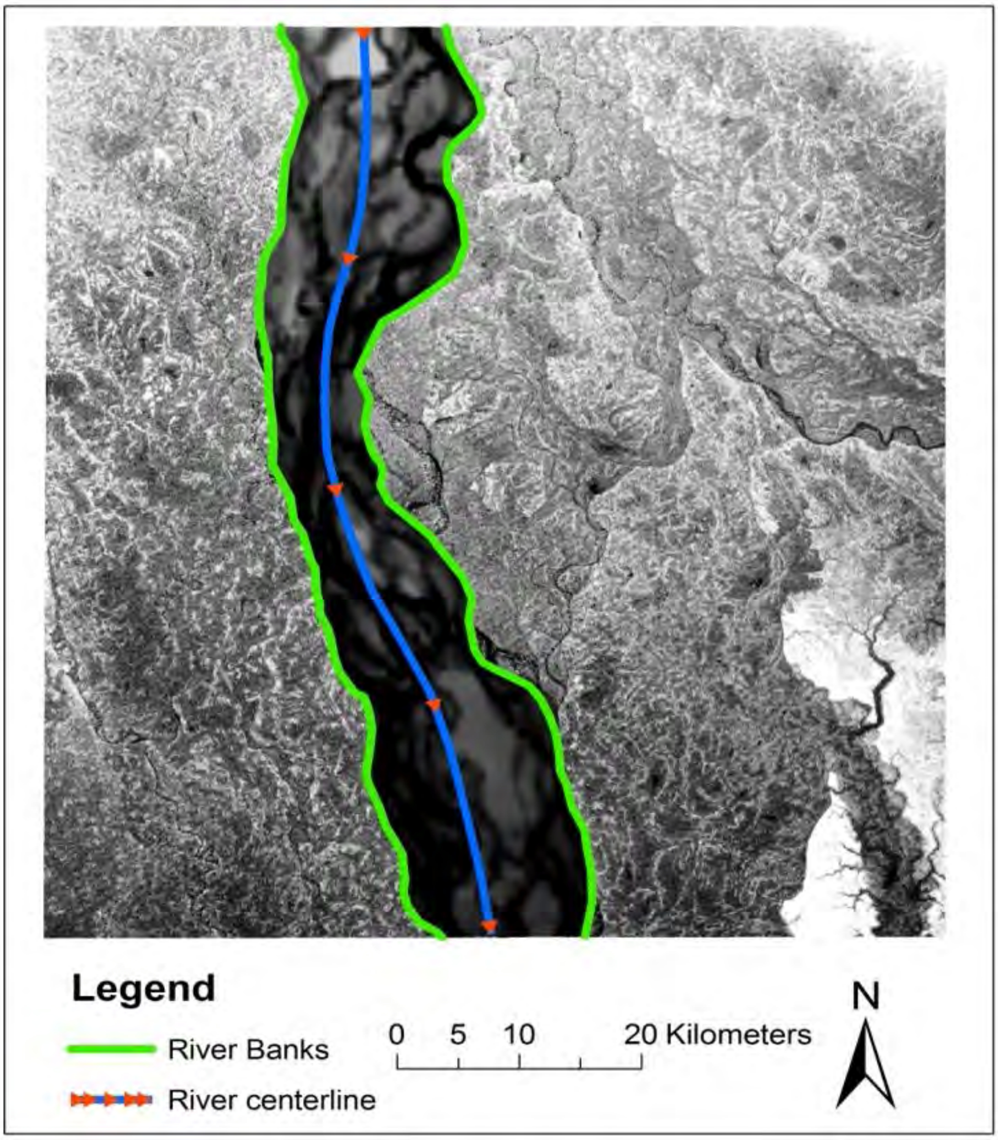


Figure 4.6: River centerline and banks line creation

create the banks theme so can be seen how accurate or inaccurate digitization ended up being.

To start editing, the first it was ensured that the “Target” menu will be set as “river banks”. The upper left corner of the view was zoomed and the theme was digitized. In digitizing, the right button on the mouse was clicked on, and also the pan to continuously digitize the line. Remember to keep the GRID coverage on to use as a reference. Look for differences in the shading of the GRIDs contours to identify the stream channel. Once completing a line in the theme, the final point was double clicked. Once the theme has been completed, under the edit menu edits were saved creating the river banks line (figure 4.6).

Flowpath creation

The Flowpath Centerlines theme is used to identify the hydraulic flowpath in the left overbank, main channel, and right overbank. If the stream centerline already exists (as in our case), copy option have to copy the river centerline for the flowpath of the main channel. To accomplish this, click on the **Create Flowpaths** command under the **preRAS** menu. Specify the name of the theme as **flowpath.shp**. The following window will then appear in Arcview (figure 4.7). Click on **Yes**, and the features of the

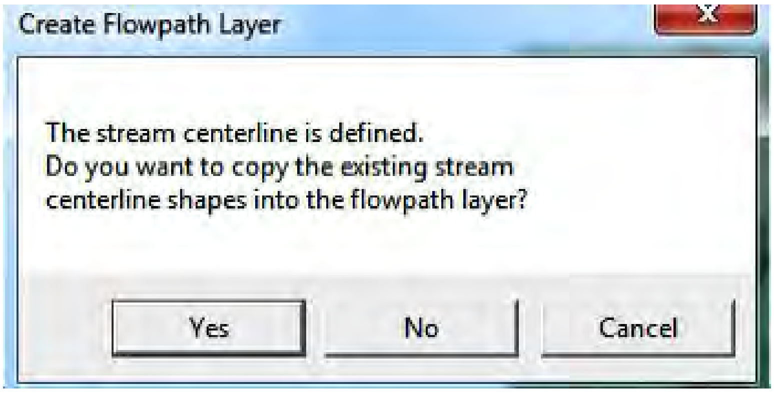


Figure 4.7: HEC-GeoRAS: creating flowpath theme

jamuna.shp will be copied to the flowpath theme. To complete the theme, digitize the flowpaths for the left and right overbanks while the **flowpath.shp** theme is in the edit mode. Make sure to adhere to the following rules regarding flowpath development:

Rules:

- All flowpaths (left overbank, main channel, and right overbank) are drawn from upstream to downstream. Changing the line symbol in the **Legend Editor** to a line with arrows can provide a visual representation of the direction of the flowpaths. The arrows should point towards downstream. If the flowpath is in the wrong direction, use the **Flip Polyline** command from the **GeoRAS-Util** menu.

- All three flowpaths should ensured at each cross section. The flowpaths are used to derive downstream reach lengths in HEC-RAS.

It is needed to be concerned with the buildings in the GRID. Once the polyline theme was completed, edit under the **Edit** menu was saved. It should be noticed that the three flowpaths for each reach, flowing from upstream to downstream. Once the digitizing the flowpaths were completed, each flowpath must now be identified as a left, right, or channel flowpath. Obviously the channel is the flowpath along the center of the river channel. Determining the left and right flowpath is accomplished by an upstream to downstream perspective. Flowpaths are shown in figure 4.8.

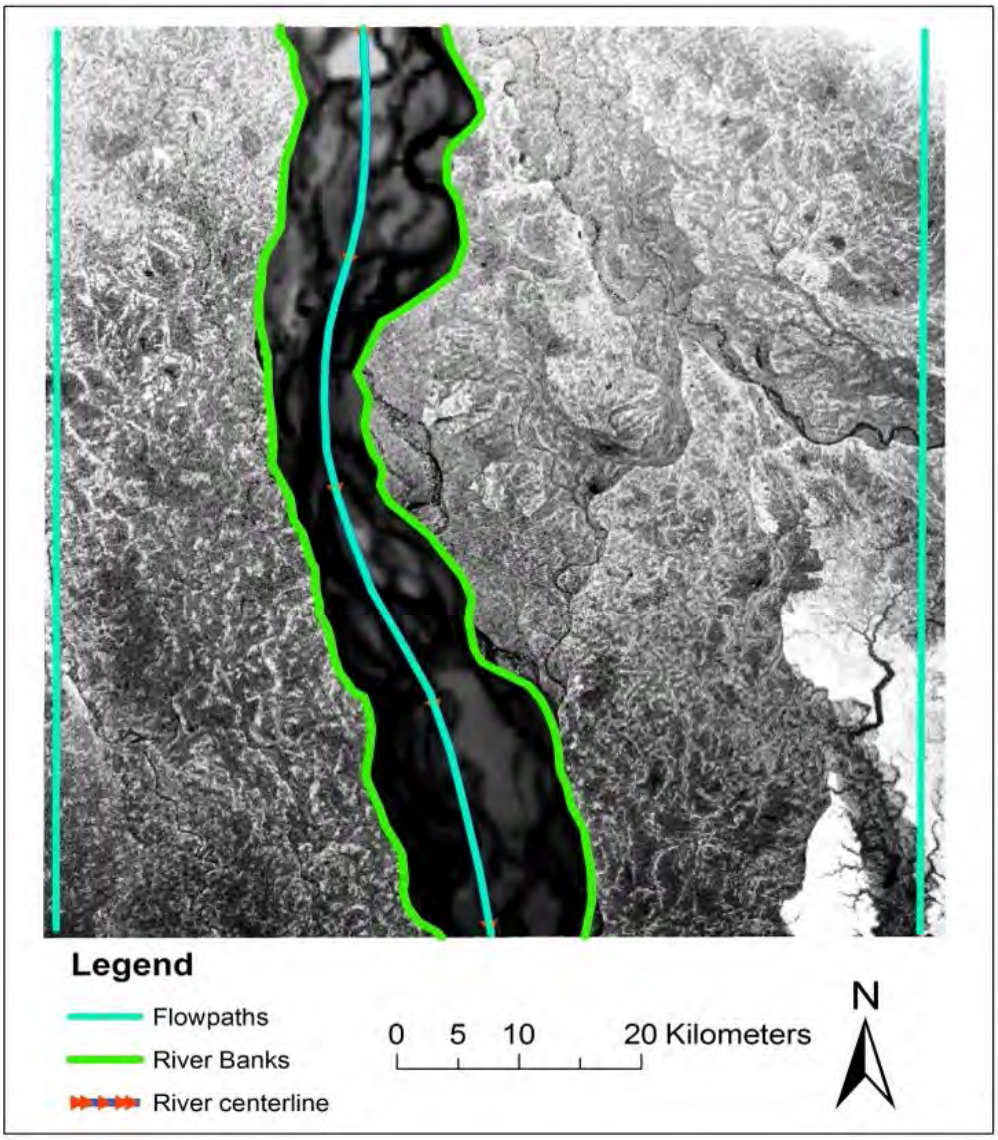


Figure 4.8: Flowpath

Cross section cut lines creation

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

Rules:

- Cross sectional cut lines must be pointed from the left overbank to the right overbank. Thus, draw each cut line from left to right, as it could look downstream.
- As it could look at the **Preprocess View**, that would be from right to left. Cross sectional cut lines must cross each of the three flowpaths and the two banks exactly once.
- Cross sectional cut lines should be perpendicular to the direction of flow. (In some cases, this might be difficult to accomplish and still follow the other rules.) Cross sectional cut lines should not intersect.

To begin digitizing the Cross Section Cut Line theme, choose the **Create XS Cut Lines** command from the preRAS menu. The theme name was specified as **xscutlines.shp** and begin digitizing. Fifty six cross-section locations were chosen for the total study reach. The distances between two consecutive cross sections were taken about 1.5 kilometers. When accomplishing this in the edit mode, the starting location was clicked on and was double clicked where each line ends.
There are four key points to remember:

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

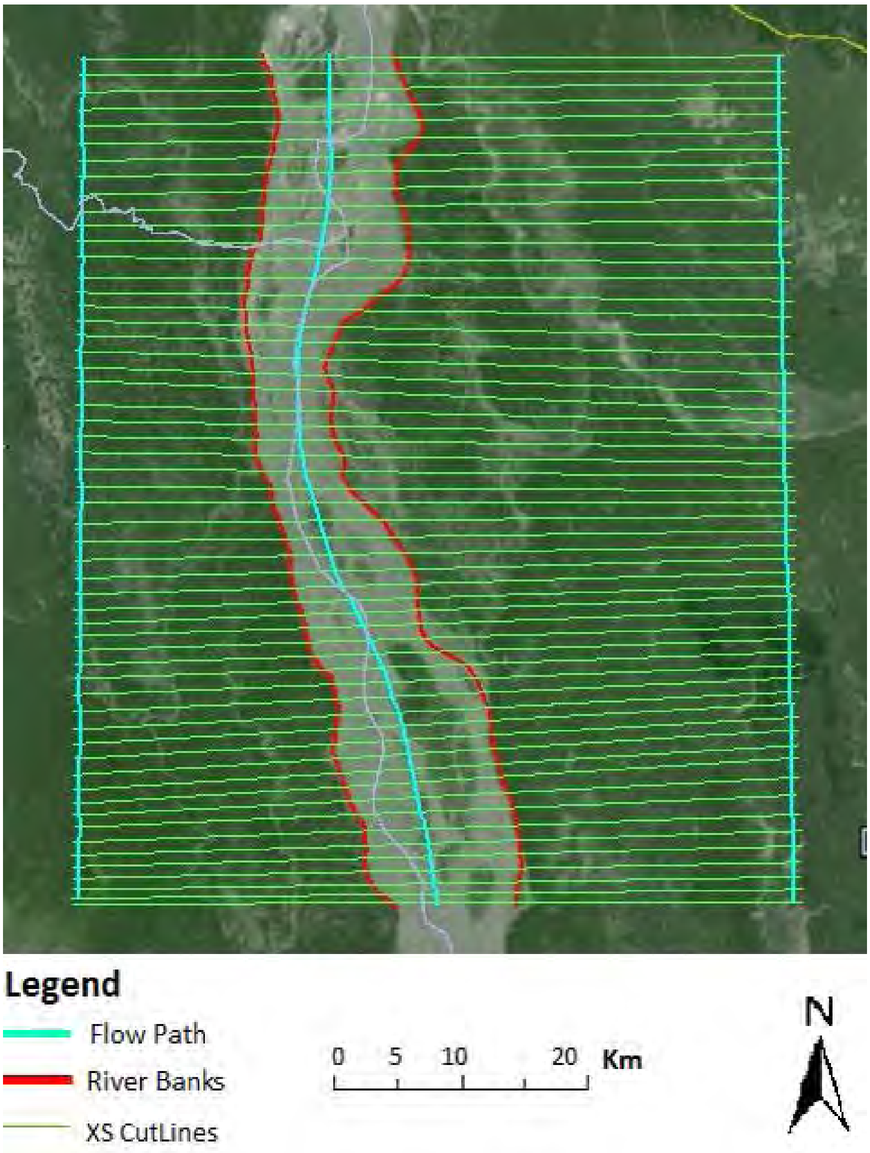


Figure 4.9: Creation of cross section

The river cross sections have been shown in figure 4.9.

4.5.2 Generation of Additional Attributes and 3D Spatial Data

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

Centerline completion

To complete the centerline theme, from the RAS Geometry menu “All” button under “Stream Centerline Attributes” was clicked. The attribute table was checked to ensure the data were properly extracted.

Cross section attributing

From the “RAS Geometry” toolbar “All” button under the “XS Cut Line Attributes was clicked to complete the cross section layer. The 2D feature class XSCutLines was intersected with the GRID to create a feature class with 3D cross section. After that, the attribute table and cross-sections are examined in order to check their correctness. Figures 4.10 and 4.11 show examples of an adequately populated attribute table of XSCutLines and of an adequate definition of cross-section, respectively.

Attributes of XSCutLines3D

Shape *	OBJECTID *	Shape_Length	XS2DID	HydroID	Station	River	Reach	LeftBank	RightBank	LLength	ChLength	RLength	NodeName
Polyline Z	18	72428.003988	21	78	55700.891	Jamuna	Reach 1	0.23972	0.36148	1863.301	1638.138	1530.705	<Null>
Polyline Z	19	72646.497597	22	79	54062.75	Jamuna	Reach 1	0.2459	0.35252	1802.006	1613.692	1528.828	<Null>
Polyline Z	20	72587.042849	23	80	52449.059	Jamuna	Reach 1	0.24744	0.35128	1660.7	1420.356	1313.478	<Null>
Polyline Z	21	72393.104542	24	81	51028.703	Jamuna	Reach 1	0.24684	0.35895	1190.343	1995.367	2351.141	<Null>
Polyline Z	22	72560.852753	25	82	49033.336	Jamuna	Reach 1	0.25108	0.35749	1253.561	1438.531	1517.247	<Null>
Polyline Z	23	72207.91875	26	83	47594.805	Jamuna	Reach 1	0.25077	0.35698	1180.479	1418.588	1522.172	<Null>
Polyline Z	24	72270.375237	27	84	46176.219	Jamuna	Reach 1	0.25116	0.36178	1457.907	1536.228	1524.89	<Null>
Polyline Z	25	72199.941686	28	85	44639.988	Jamuna	Reach 1	0.25085	0.37487	1316.657	1497.259	1523.692	<Null>
Polyline Z	26	72404.673233	29	86	43142.73	Jamuna	Reach 1	0.26115	0.37409	1321.515	1692.349	1796.72	<Null>
Polyline Z	27	72399.800663	30	87	41450.383	Jamuna	Reach 1	0.2701	0.37957	1183.245	1477.778	1522.382	<Null>
Polyline Z	28	72259.748249	31	88	39972.605	Jamuna	Reach 1	0.27427	0.40087	1256.919	1784.738	1935.385	<Null>
Polyline Z	29	72469.576451	32	89	38187.867	Jamuna	Reach 1	0.2849	0.42475	1390.028	1745.39	1797.71	<Null>
Polyline Z	30	72404.673233	33	90	36442.477	Jamuna	Reach 1	0.29253	0.44305	1391.51	1696.756	1730.755	<Null>
Polyline Z	31	72410.142151	34	91	34745.719	Jamuna	Reach 1	0.29935	0.45757	1250.641	1637.396	1730.66	<Null>
Polyline Z	32	72212.804265	35	92	33108.324	Jamuna	Reach 1	0.30019	0.46983	1317.117	1585.812	1519.253	<Null>
Polyline Z	33	72287.541325	36	93	31522.512	Jamuna	Reach 1	0.30591	0.47778	1249.585	1529.72	1451.317	<Null>
Polyline Z	34	72362.864592	37	94	29992.793	Jamuna	Reach 1	0.30974	0.47585	974.094	1314.134	1315.969	<Null>
Polyline Z	35	72305.068442	38	95	28678.658	Jamuna	Reach 1	0.31599	0.47625	1401.794	1411.936	1195.455	<Null>
Polyline Z	36	72367.242208	39	96	27266.723	Jamuna	Reach 1	0.31859	0.47794	1449.075	1514.405	1319.339	<Null>
Polyline Z	37	72155.120741	40	97	25752.318	Jamuna	Reach 1	0.32268	0.48548	1248.857	1464.999	1382.679	<Null>
Polyline Z	38	72228.75467	41	98	24287.318	Jamuna	Reach 1	0.3307	0.50927	1254.995	1424.574	1318.302	<Null>

Record: 55 Show: All Selected Records (1 out of 56 Selected) Options

Figure 4.10: Example of adequately populated attribute table of XSCutLines

4.5.3 Exporting GIS Data to HEC-RAS

The generation of the HEC-RAS import file was the last step of the HEC-GeoRAS pre-processing. The idea was to create a HEC-RAS input file in RAS Import format which includes the terrain elevation extracted from the GRID, the 3-D stream centerline and

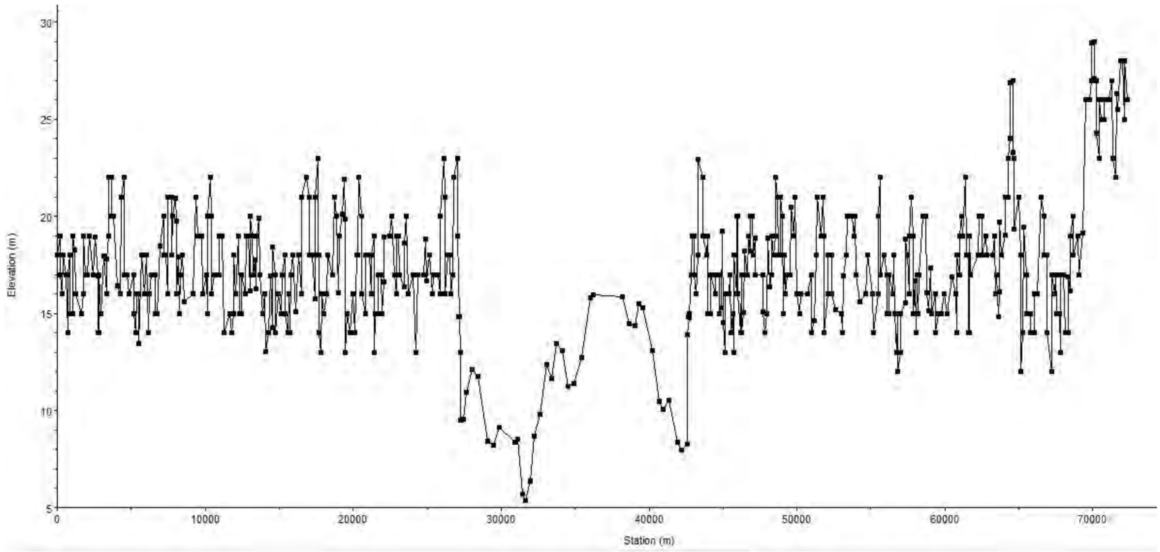


Figure 4.11: Example of adequate definition of cross-section

the 3-D cross sections themes as z values (z value is the elevation above mean sea level and, for our case, is in units of meter). The "Extract GIS DATA" was clicked under the menu "RAS Geometry" from the HEC-GeoRas toolbar. The default name GIS2RAS was accepted and saved in the selected folder.

4.6 Model performance Evaluation

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.

4.6.1 Coefficient of determination (R^2)

Coefficient of determination (R^2) describe the degree of collinearity between simulated and measured data. R^2 ranges from 0 to 1, with higher values indicating less error variance and typically values greater than 0.5 are considered acceptable (Moriasi *et al.* 2002, 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):

$$r = \frac{n\sum(xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \tag{4.7}$$

where x is the observation and y is the simulated value for the constituent being evaluated.
Coefficient of determination $R^2 = r^2$

4.6.2 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 is computed as shown in equation 4.8.

$$NSE = 1 - [\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})^2}] \tag{4.8}$$

where Y_i^{obs} is the i-th observation for the constituent being evaluated, Y_i^{sim} is the i-th 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. 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.

Chapter 5

Model Development

5.1 Geometry data in HEC-RAS

HEC-RAS is an integrated software system, designed for interactive use in a multi-tasking environment and used to perform one-dimensional water surface calculations. Four files are required to run a HEC-RAS project. First, the 'Project File' that acts as a file management tool and identifies which files are used in the model. The 'Plan File' sets the model conditions as subcritical, supercritical, or mixed flow and runs the simulation. The 'Geometry File' contains all the geometric attributes for the model. The 'Steady Flow File' establishes the steady-state flow and boundary conditions at numerous points in time for the model. The 'Unsteady Flow' File establishes the unsteady-state flow and boundary conditions at numerous points in time for the model.

5.1.1 Importing geometry data

The geometric data editor was opened from the project window. The 'import GIS data' from the 'File' menu was opened. This operation needs to specify the unit system. The unit system was selected as SI units. All the data appears in the geometric data editor (figure 5.1). Amongst the geometric data, a typical cross section has been shown in figure 5.2.

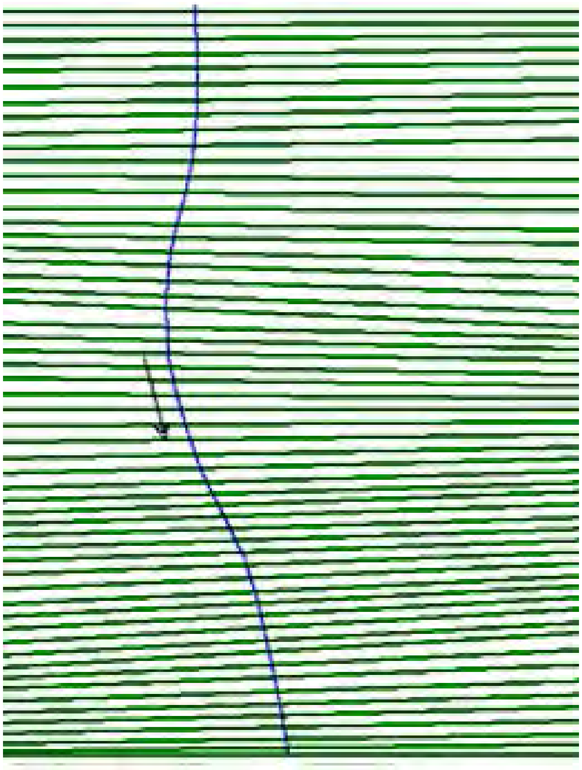


Figure 5.1: Imported geometric data from GIS

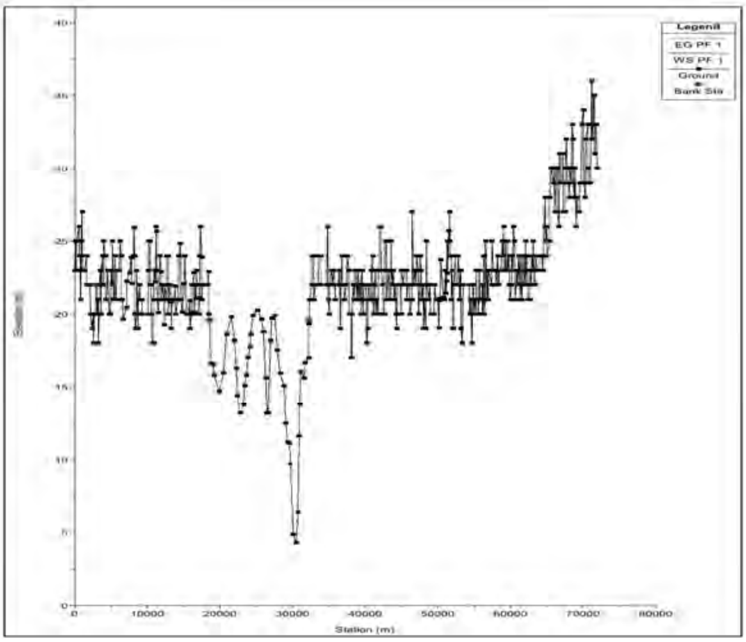


Figure 5.2: Extracted cross-section from GRID

5.2 River's levee setup

Levees are digitized to limit flow in the overbanks. The levee information is extracted at each cross-sectional cut line intersected by a levee. At first, river's bankfull height is considered as a levee elevation. The bankfull discharge for the Jamuna River is 48,000 cumec (Islam 2012). A steady flow has been simulated using bankfull discharge to generate a bankfull water level. This water level height has been used as a levee elevation. The levee elevation underestimates with the known levee elevation at Bahadurabad, Sirajganj, Mathurapara and Kazipara stations. The levee elevation for Bahadurabad, Mathurapara, Kazipara, and Sirajganj stations are 19.50, 16.70, 14.85 and 13.35 m respectively. This data have been collected from Bangladesh Flood Forecasting and Warning Centre (FFWC). A slope has been made using these four stations' levee elevations. Finally, these known levee elevation has been used as a levee elevation for modeling.

5.3 Boundary condition

Boundary condition is the conditions or phenomenon occurring at the boundaries of the model. The data of 2004 and 2005 have been used as a boundary condition for calibration and validation respectively for both steady and unsteady flow simulations.

5.3.1 Boundary condition for steady flow analysis

In steady flow analysis, discharge data have been used as an upstream boundary and known water level data have been used as downstream boundary condition. Data for the years of 2004 and 2005 have been used for calibration and validation correspondingly. Model boundary locations are shown in figure 5.3. Table 5.1 shows the boundary condition data for calibration and table 5.2 shows the boundary condition data for validation.

5.3.2 Boundary condition for unsteady analysis

The one-dimensional model has one upstream discharge boundary and one downstream water level boundary. To calibrate the model, the boundary conditions have been used

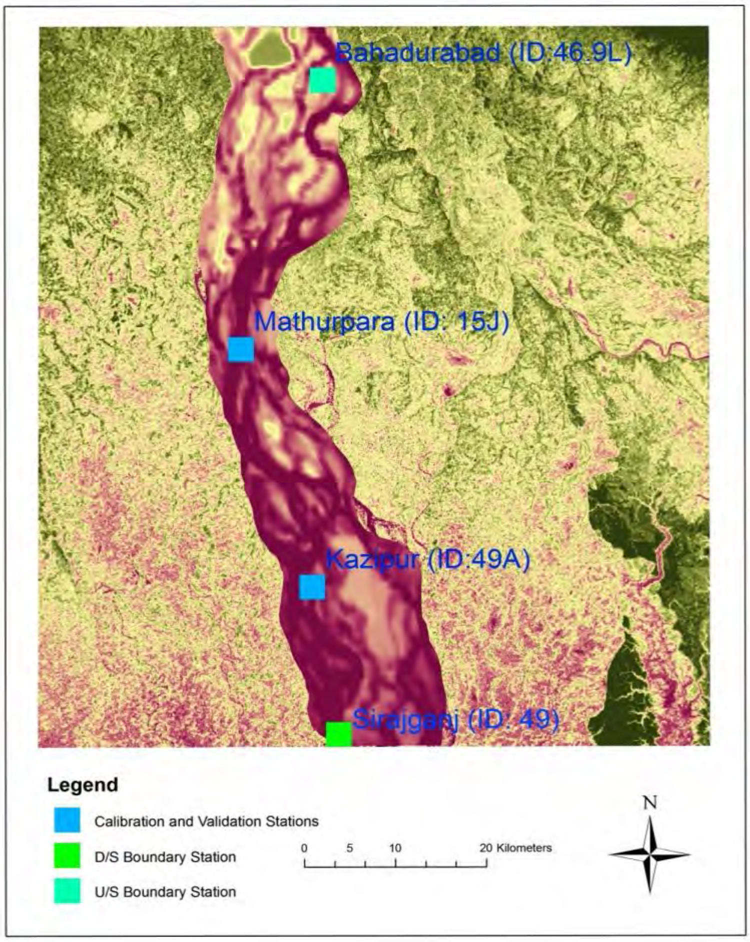


Figure 5.3: Model boundary, calibration, and validation stations

S

Table 5.1: Boundary condition for steady flow calibration (2004)

Profile	U/S Boundary Condition Discharge (cumec)	D/S Boundary Condition WL (m)
Profile 1 (P1) Low Flow	4773	7.37
Profile 2 (P2) Mean Flow	23616	10.41
Profile 3 (P3) Maximum Flow	83915	14.71

Table 5.2: Boundary condition for steady flow validation (2005)

Profile	U/S Boundary Condition Discharge (cumec)	D/S Boundary Condition WL (m)
Profile 1 (P1) Low Flow	6535	7.46
Profile 2 (P2) Mean Flow	21823	10.36
Profile 3 (P3) Maximum Flow	55340	13.31

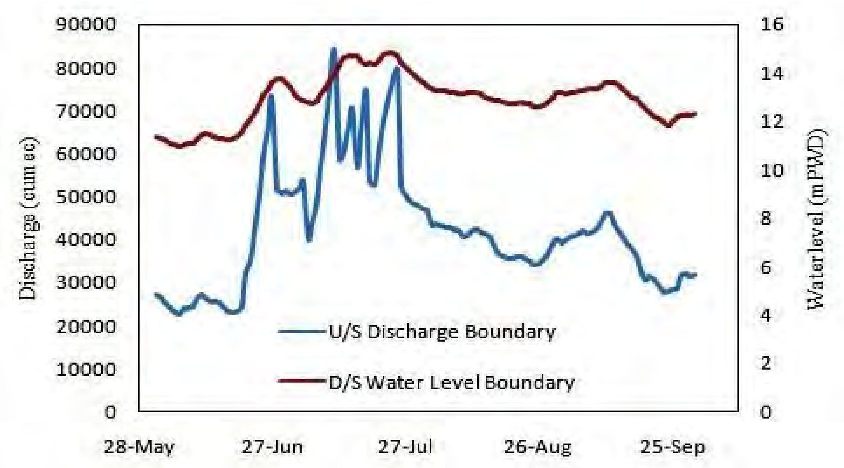


Figure 5.4: Model u/s and d/s boundary for unsteady flow calibration (2004)

from the observed data for the year of 2004. To validate the model, the boundary conditions have been used from the observed data for the year of 2005. The upstream discharge boundary and downstream water level boundary for calibration and validation are shown in figure 5.4 and 5.5 respectively. Finally, a discharge data have been used as an initial condition.

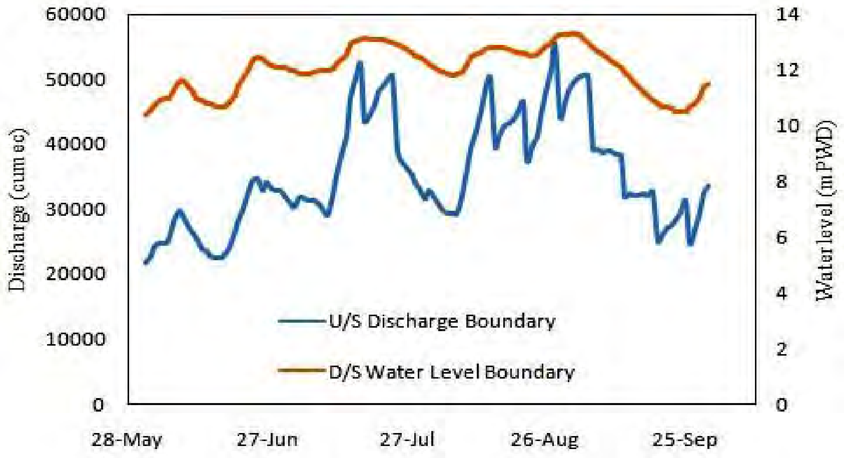


Figure 5.5: Model u/s and d/s boundary for unsteady flow validation (2005)

5.4 Model calibration

To simulate the model with base and different flow conditions, it is necessary to test the model's performance. A set 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 one-dimensional HEC-RAS model has been calibrated hydro-dynamically.

Steady flow calibration

Hydrodynamic calibration is done with the fixed bed model. Water level calibralion has been done at two stations namely Kazipur and Mathurapara (figure: 5.3). The hydrodynamic calibration mainly involves adjustment of bed resistant (Manning's "n"). Number of trial simulations were performed to verify the selection of the 'n' and finally 'n' value as 0.022 for main channel and 'n' value as 0.037 for flood plain has been fixed as Manning's 'n'. Steady flow calibration is shown in figure 5.6 and statistical parameter is shown in figure 5.7. Coefficient of determination (R^2) have been found 0.985 for the steady flow calibration. Figure 5.6 shows the simulation of flood flow

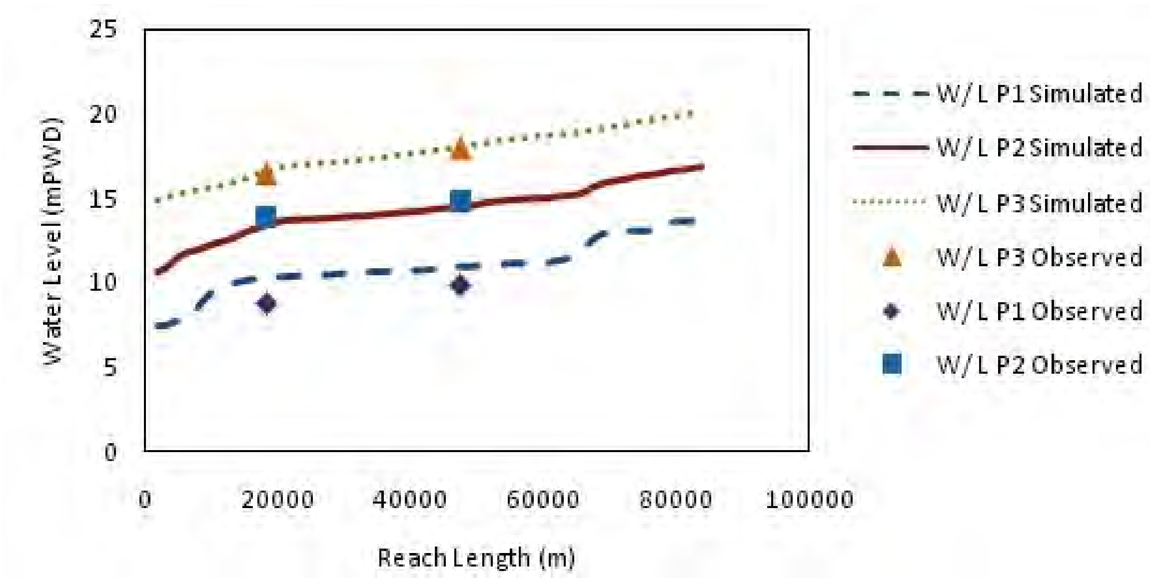


Figure 5.6: Observed and simulated water level (calibration) (2004)

is best fitted with observed data where as the low flow simulation overestimate with the observed data. Maximum and medium flow simulations are better fitted to the observed data.

Unsteady flow calibration

The data regarding to the flood year 2004 has been used for calibration of Manning's roughness coefficient 'n'. The model has been simulated using the daily hydrograph for four months from June to September. For this study, effort has been made to calibrate Manning's roughness coefficient for single value using aforesaid data and subsequently, different values have been used to justify their adequacy for simulation of flow in the Jamuna River. Finally, 'n' value as 0.022 for main channel and 'n' value as 0.037 for flood plain has been fixed as Manning's 'n'. The comparison of observed and simulated stage hydrograph at Kazipur and Mathurapara gauging station for Manning's 'n' value of 0.022 for main channel and 0.037 for flood plain is shown in figure 5.8 and 5.9 respectively. Further, considering Manning's 'n' value as 0.022 for main channel and 0.037 for flood plain, the flood peak and time to peak for the flood year 2004 is computed and it is observed that there is a close agreement between the observed and computed values. Typical value of Manning's roughness coefficient 'n' is 0.025 for river and 0.040 for flood plain (Chow *et al.* 1988) which indicate our Manning's value is acceptable.

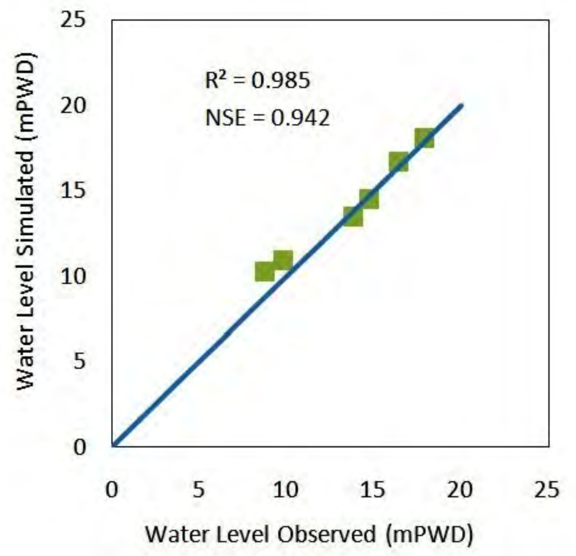


Figure 5.7: Statistical parameter of steady flow calibration for the of 2004

In steady calibration, the coefficient of determination R^2 and the value of Nash and Sutcliffe Efficiency (NSE) have been found 0.942 and 0.985 respectively which are adequate (figure 5.7).

In unsteady calibration, the coefficient of determination R^2 and Nash and Sutcliffe Efficiency (NSE) have been found 0.821 and 0.65 respectively which indicate, the simulated value is closer to the observed value (figure 5.10).

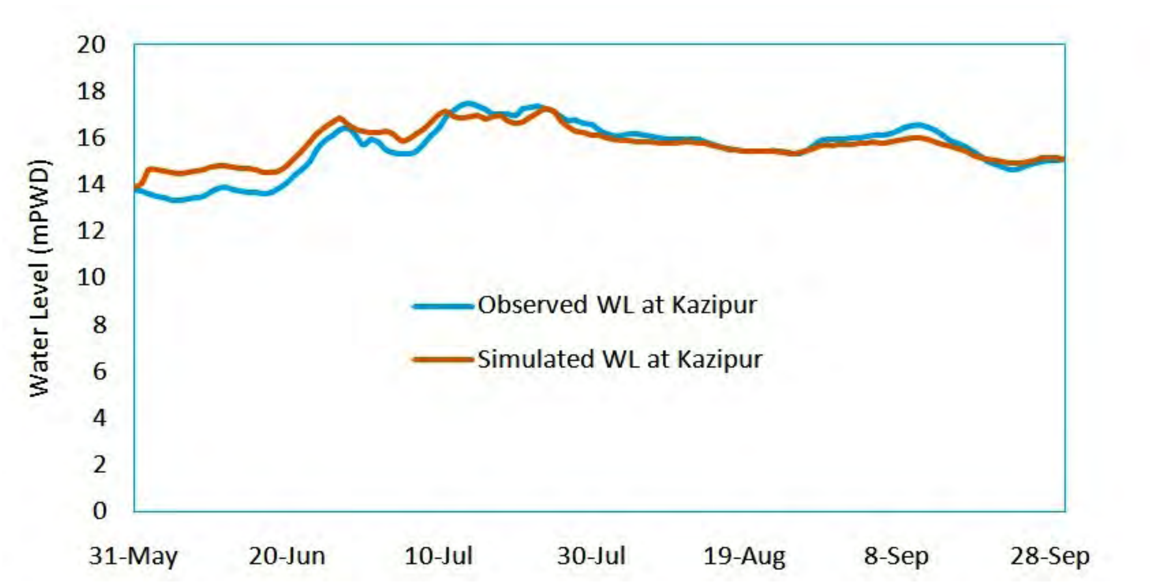


Figure 5.8: Observed and simulated hydrograph at Kazipur (calibration) (2004)

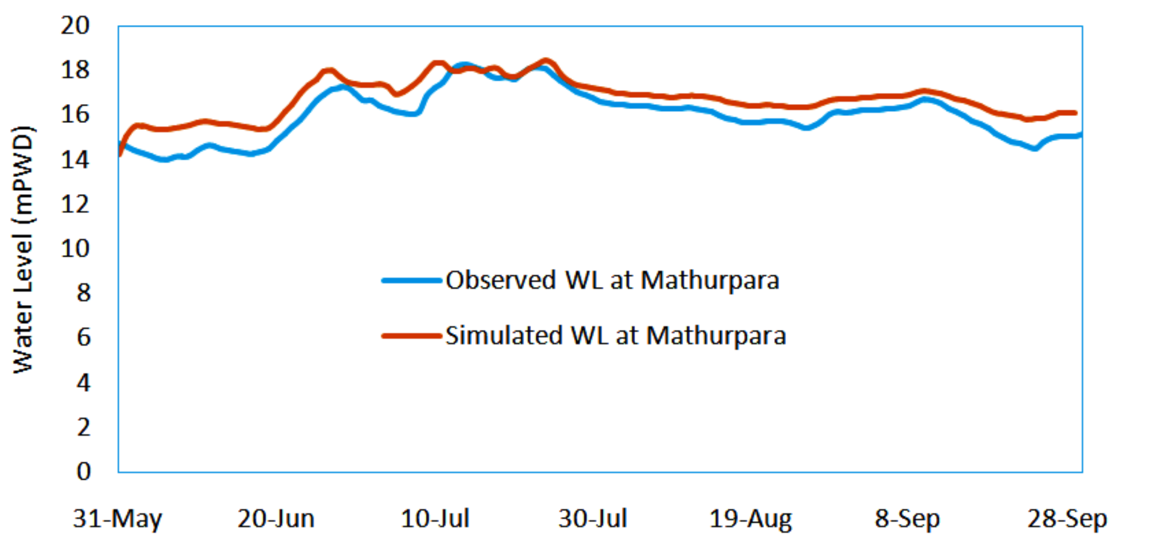


Figure 5.9: Observed and Simulation Hydrograph at Mathurapara (Calibration) (2004)

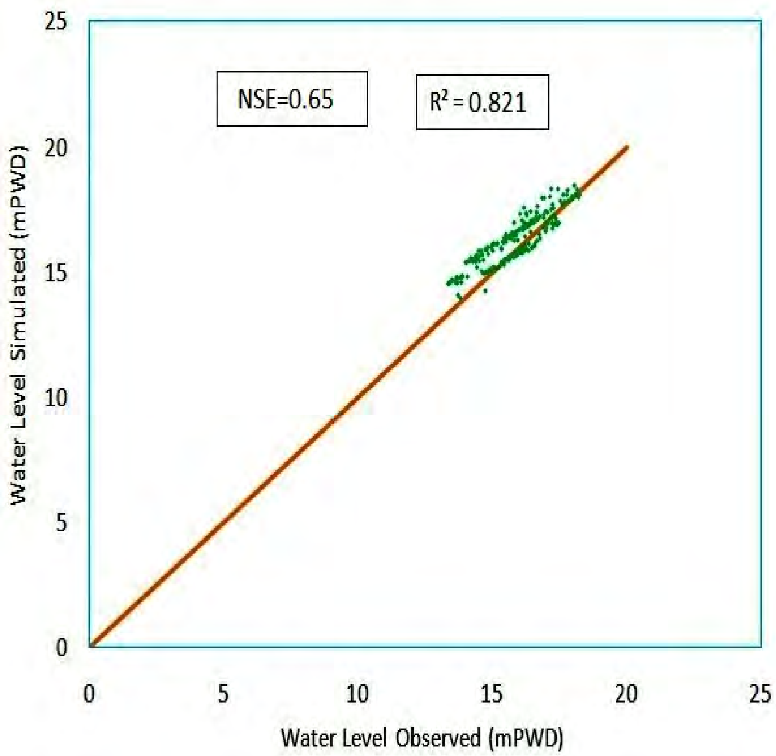


Figure 5.10: Statistical parameter of unsteady flow calibration for the of 2004

5.5 Model validation

Model validation involves testing of a model with a data set representing 'observed' field data. This data set represents an independent source different from the data used to calibrate the model. Due to the uncertainty of prediction, this step is very important prior to widespread application of model output. The calibrated HEC-RAS based model has been used to validate the flow for the year 2005.

Steady flow validation

The comparison of observed and simulated flow at Kazipur and Mathurapara gauging stations are shown in figure 5.11. From the figure it is shown that the observed data are in close agreement with the observed data. The value of coefficient of determination R^2 and Nash and Sutcliffe Efficiency (NSE) have been found 0.977 and 0.911 respectively (figure 5.12).

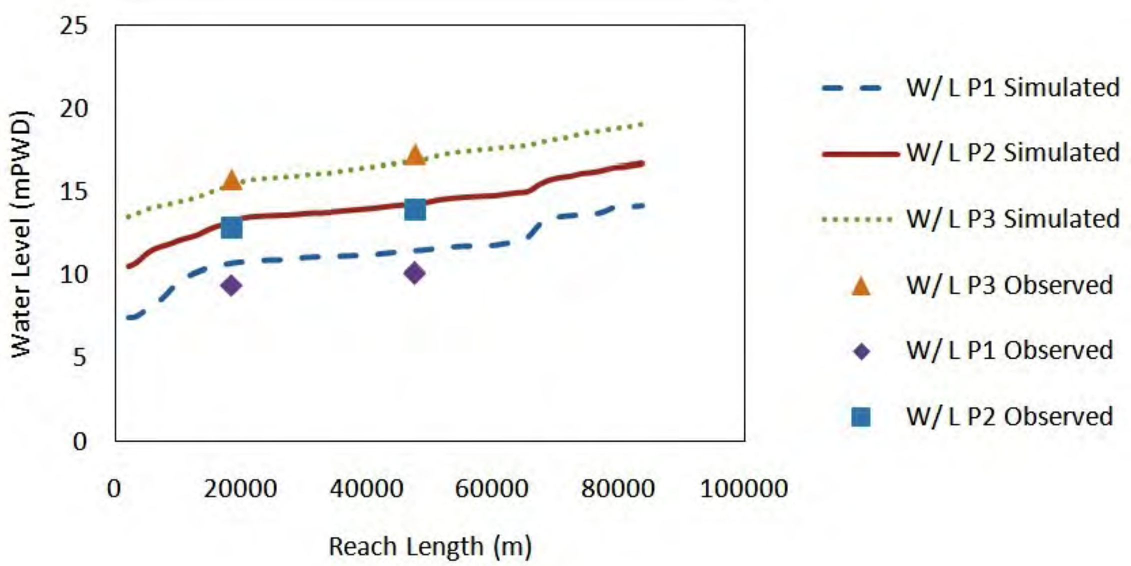


Figure 5.11: Observed and simulated water level (validation) (2005)

Unsteady flow validation

The comparison of observed and simulated flow hydrograph at Kazipur and Mathurapara gauging stations are shown in Figure 5.13 and 5.14 respectively. The figure shows the simulated flood hydrograph is in close agreement with observed hydrograph. NSE

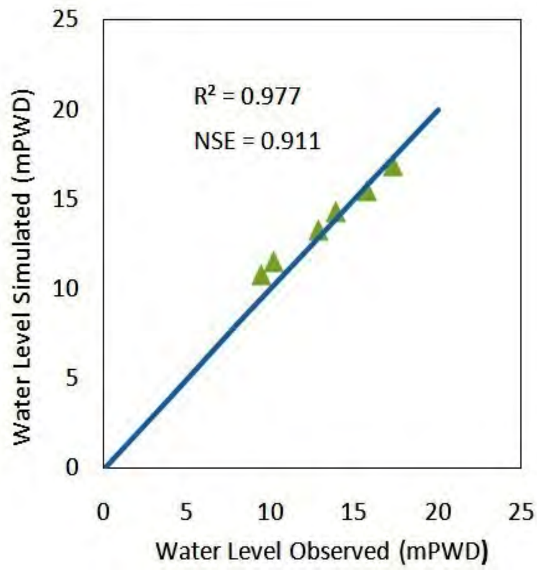


Figure 5.12: Steady flow validation statistical parameter of the Jamuna River (2005)

and R^2 values have been found 0.63 and 0.811 respectively 5.15.

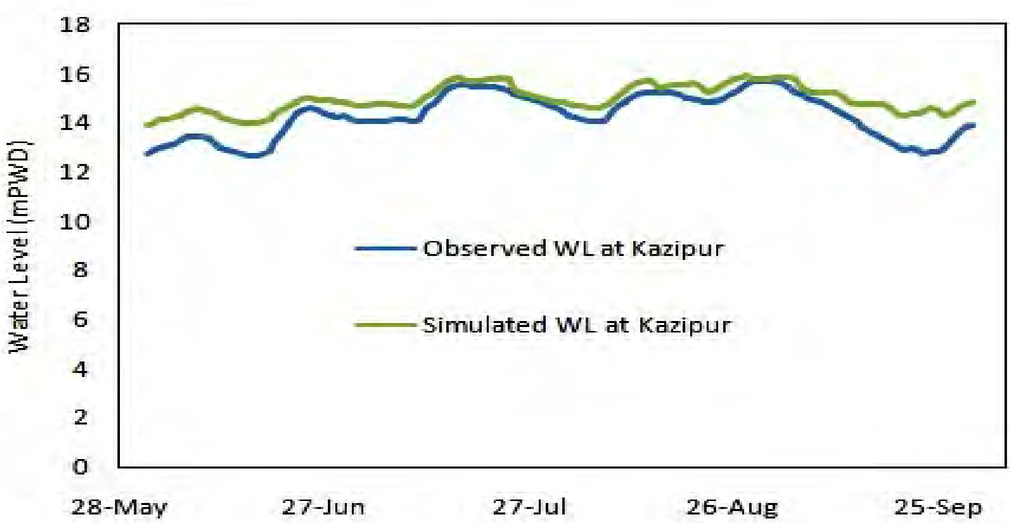


Figure 5.13: Observed and simulation hydrograph at Kazipur (validation) (2005)

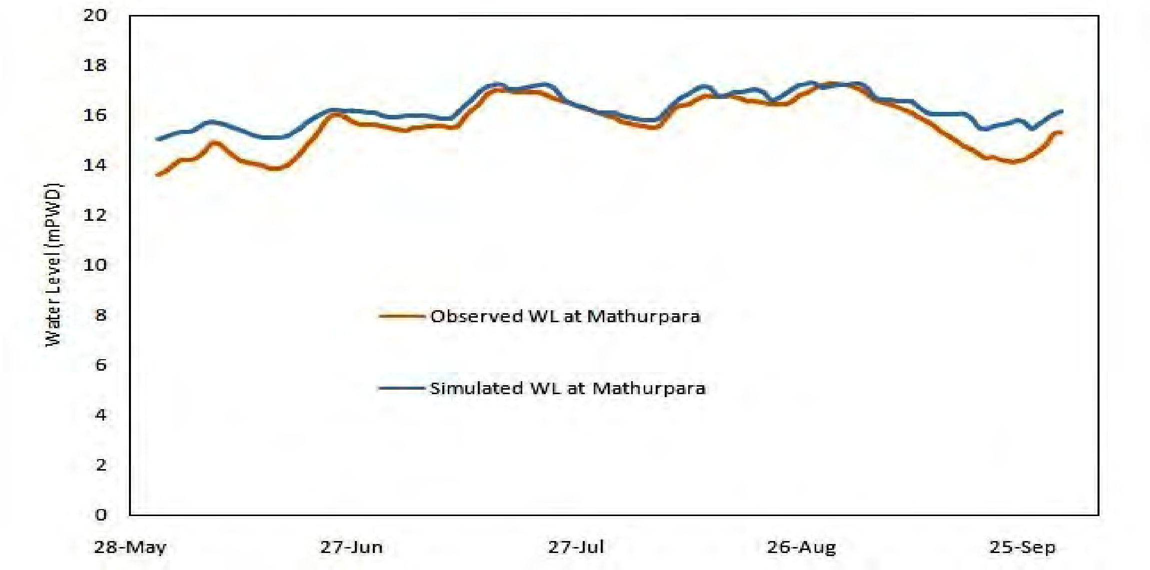


Figure 5.14: Observed and simulated hydrograph at Mathurapara (validation) (2005)

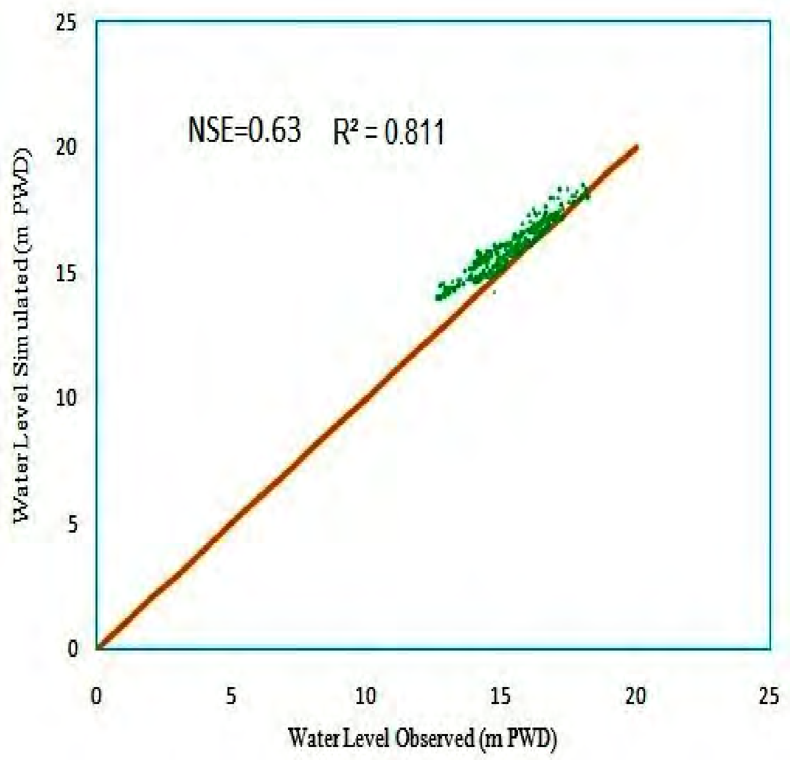


Figure 5.15: Unsteady flow validation statistical parameter of the Jamuna River (2005)

Steady and Unsteady flow calibration and validation statistical parameter are summarized in table: 5.3.

Table 5.3: Model evaluation parameters

	Flow condition	R^2	**NSE**
Calibration (2004)	steady	0.985	0.942
	unsteady	0.821	0.650
Validation (2005)	steady	0.977	0.911
	unsteady	0.811	0.630

5.6 Water surface profiles generation

The calibrated and validated model has been used to generate water surface profiles for different flow conditions. At first, 2004 flood discharge water profile has been generated. Then, flood frequency analysis of 2, 5, 10, 25, 50 and 100 year return periods were calculated. The water profiles of these return period discharge data have been generated. Finally, water surface profiles of five-day-interval from June 15 to October 15 have been generated for five years from 2001 to 2005. The generated water surface profile data have been exporting in GIS format data to develop flood inundation map.

5.7 Post-processing of HEC-RAS results and flood-plain mapping

The post-processing of computation results is performed using the same maps which where used for the pre-processing of geometry data. The only additions to these maps are new map layers. Detail explanation of data post-processing are given below.

5.7.1 Data import from HEC-RAS

Formatting

The process starts with opening a desired ArcMap for post-processing. Since the HEC-GeoRAS cannot read the proprietary spatial data format (RASExport.sdf) file, created in the HEC-RAS, it is necessary to convert it into the XML file format, supported by HEC-GeoRAS. This is achieved by selecting the "Import RAS SDF File" option from the HEC-GeoRAS Toolbar.

Layer setup

Establishing the Layer Setup is a necessary step for processing the HEC-RAS results. In the Layer Setup window, the type of analysis and the input and output data are identified. For the post-processing analyses, the rasterization cell size is set to 10 map units. Basically, a smaller number of map units results in a better representation of the resulting floodplain boundary during the floodplain delineation.

5.7.2 Floodplain mapping

Floodplain mapping is performed using the water surface elevations on the XS cut lines, within the limits of the bounding polygon. Floodplain mapping is completed in two steps, which are explained in the following paragraphs.

Water surface generation

The first step is to create a water surface TIN from the cross section water surface elevations. To generate water surface TIN, "Water Surface Generation" button is clicked from the HEC-GeoRAS tool bar. For each selected water surface profile, a water surface TIN is created without consideration of the terrain model. The TIN is created using the ArcGIS triangulation method. This is allowed for the creation of a surface using cut lines as hard break lines with constant elevation.

Floodplain delineation

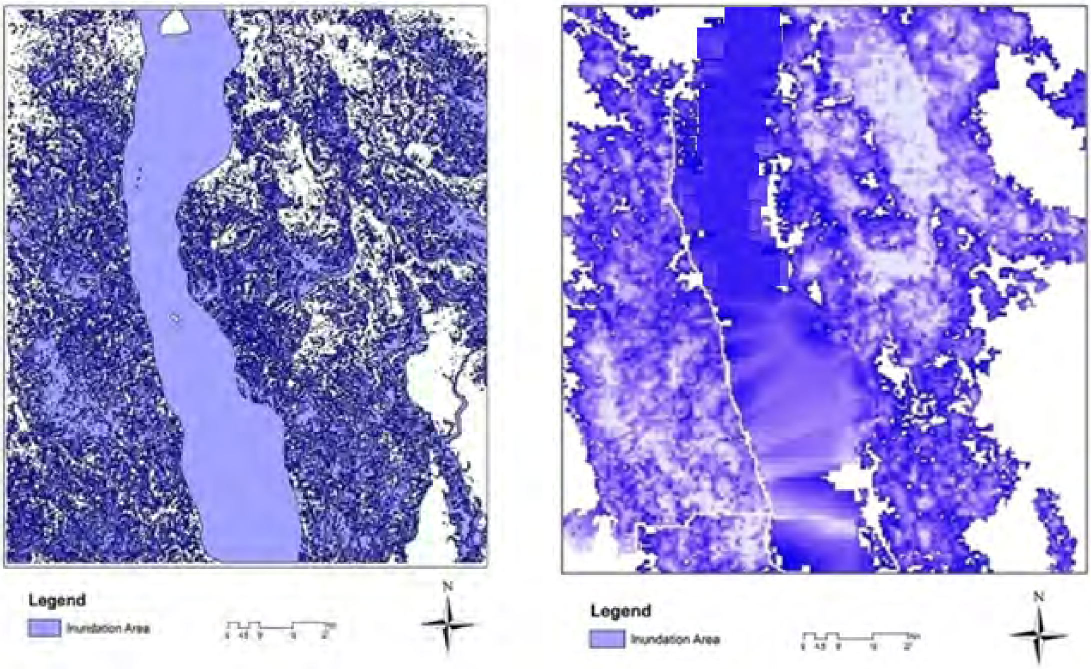
This is the final step to generate floodplain map. To generate water surface TIN, 'Inundation Mapping' button is clicked from the HEC-GeoRAS tool bar to generate the floodplain map. The water surface TIN is converted into a grid based on the rasterization cell size. Then, it is compared with the TIN terrain model, which is also in grid format, allowing the elevation difference to be calculated within the bounding polygon. The areas with positive results (where water surface is higher than the terrain elevation) are included in the floodplain area (inundation depth grid) and the areas with negative results are considered as dry.

5.7.3 Qualitative comparison between model and observed flood map

After generating the flood inundation map, it is important to check the flood delineation area and depth. In this section qualitative comparison between model and observed flood maps are shown.

5.7.4 Qualitative comparison between model and observed 2004 flood map

Qualitative comparison between simulated and observed 2004 flood map is shown in figure: 5.16. Figure shows that the inundation area between simulated and observed are adequately alike.



(a) model flood map (b) observed flood map

Figure 5.16: Qualitative comparison between simulated and observed 2004 flood map

5.7.5 Qualitative comparison between model and observed 2007 flood map

Another qualitative comparison is shown between the simulated and observed flood extend area of 2007 (figure: 5.17). This figure also shows that simulated flood extend area is similar to observed flood extend area.

As a qualitative comparison between observed and simulated inundation map gives satisfactory result, steady and unsteady hydrodynamic simulation is performed. Steady

(a)simulated flood map (b) observed flood map

Figure 5.17: Qualitative comparison between simulated and observed 2007 flood map

and unsteady hydrodynamic simulation's water profile is used to generate flood inundation map. Frequency analysis of discharge data are used to perform a steady simulation. Five years from 2001 to 2005, flow hydrograph at Bahadurabad and stage hydrograph at Sirajgang station have been used as boundary conditions for unsteady simulations. Steady and unsteady flow simulations flood maps are presented and discussed in the following chapter.

Chapter 6

Results and Discussion

6.1 Introduction

After the model calibration and validation, future flow has been estimated for different return periods and flood extend and inundation maps have been prepared for those estimated flows. Unsteady simulation has been performed for analysis the changing of flood pattern with time. Finally, the levee impact on the flood inundation area has been estimated. In this chapter, results and discussions are presented detail.

6.2 Results of flood frequency analysis

The results of 2, 5, 10, 25, 50 and 100 year return period flood frequency analysis based on maximum flow recorded at Bahadurabad (Station ID 46.9L) from year 1956 to 2012 excluding 1971 using Normal Distribution (N), Log Normal (LN), Pearson Type - III Distribution (P3), Log Pearson Type - III Distribution (LP3), and Gumbel Distribution (EV1) method are summarized below in table 6.1. There is an increasing trend of discharge at Bahadurabad gauge station of the Jamuna river. For selecting best fitted distribution, goodness-of-fit test has been conducted. The values of Probability Plot Correlation Coefficient (PPCC) and Chi-Square test have been shown in table 6.1. The maximum PPCC value can be one that indicates that the method is completely fit. Again it is know that if Chi square is equal to zero the theoretical and observed frequencies agree exactly; while if chi square is greater than zero they do not agree exactly and the larger the value of Chi square the greater is discrepancy between the observed

Table 6.1: Peak discharge for various return periods at Bahadurabad

	Return Periods (years)					
Methods	2	5	10	25	50	100
N (cumec)	66912	77428	83021	89027	92905	96362
LN (cumec)	65772	76871	83519	91299	96703	101790
P3 (cumec)	65541	76798	83619	91626	97186	102411
LP3 (cumec)	66482	77613	84199	91831	97086	101999
EV1 (cumec)	64758	75923	83315	92655	99584	106461

Table 6.2: Goodness of fit test among five distributions

Tests	Normal	Log-Normal	Pearson	Log-Pearson	Gumbel
PPCC	0.9759	0.9859	0.9858	0.9854	0.9855
Chi Square	12.34	8.54	10.22	9.42	11.655

and expected frequencies. From table 6.1 it is seen that chi square is minimum for Log Normal distribution and PPCC is higher for Log Normal distribution. Considering the two goodness of fit test the Log Normal three parameters is the best distribution among the five distributions for this station discharge data . The following Probability Plots in Figure 6.1 show the Probability values using Log Normal distribution.

It is observed that flood frequency analysis by Log Normal (LN) shows discharges of 65772, 76871, 83519, 91299, 96703, and 101790 m^3/sec for 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year return periods respectively, which are lower as compared to the result obtained by Pearson Type - III Distribution (P3), Log Pearson Type - III Distribution (LP3), and Gumbel Distribution (EV1) and higher than Normal Distribution. The discharges from Log Normal (LN) distribution method have been used for future flood modeling.

6.3 Steady flow analysis and flood depth analysis

Flood extend and flood inundation depth maps have been prepared using discharges of different return periods. Further, flood inundation area has been classified according to flood water depth. The results of these assessments are discussed in the following

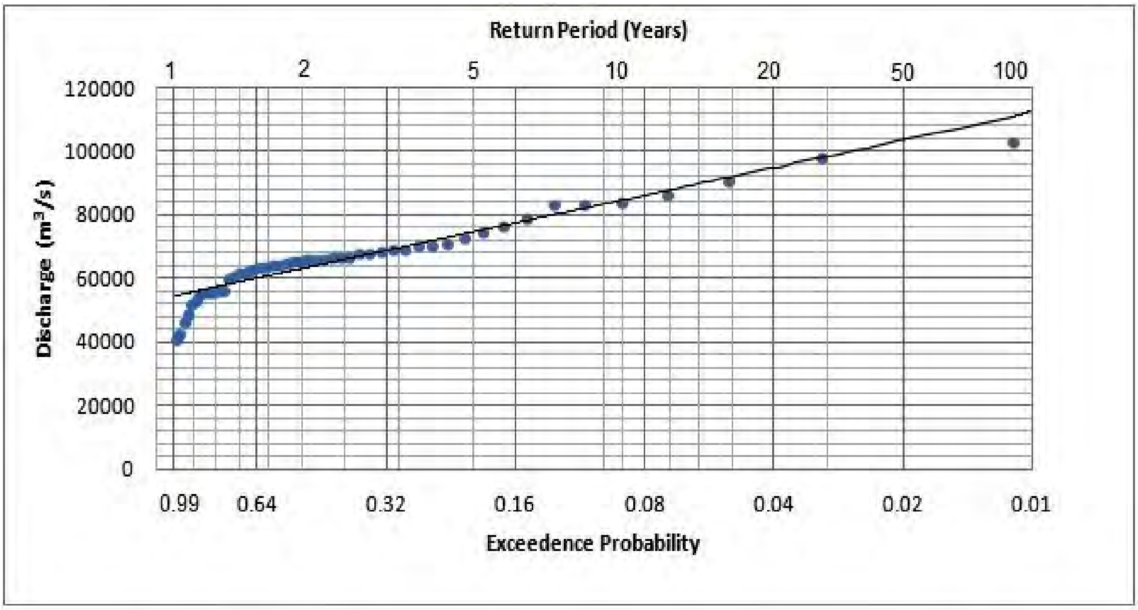


Figure 6.1: Log Normal probability plot for annual peak flows of Bahadurabad station

sub-sections.

6.3.1 Steady flow analysis

Maps of extended flood of particular return periods are shown in figure: 6.2 to figure: 6.7. Inundation area and the percentage of inundation area with return periods are shown in table: 6.3. Maximum and minimum inundation area are 59.19% for 100-year return period and 26.12% for the 2-year return period respectively. For other return periods i.e, 5, 10, 25, and 50-year % of inundation area are 46.10, 51.14, 54.63, and 56.89% respectively. The total floodplain area is about 4839 sqkm.

It is observed that the flood inundation areas are 1263.86, 2230.89, 2474.44, 2643.41, 2752.97 and 2864.34 square kilometers (sqkm) for 2, 5, 10, 25, 50 and 100-year return periods respectively. Figure 6.8 shows the relationship between inundation area and return periods. From the figure it can be seen that inundation area increases.

Steady Flow Analysis performed in HEC-RAS shows discharges of 65772, 76871, 83519, 91299, 96703, and 101790 cumec which inundate 1264, 2231, 2474, 2643, 2753, and 2864 sqkm area respectively. Area inundated with respect to discharge shows that there is a slight increase in the inundated area (Fig: 6.9).

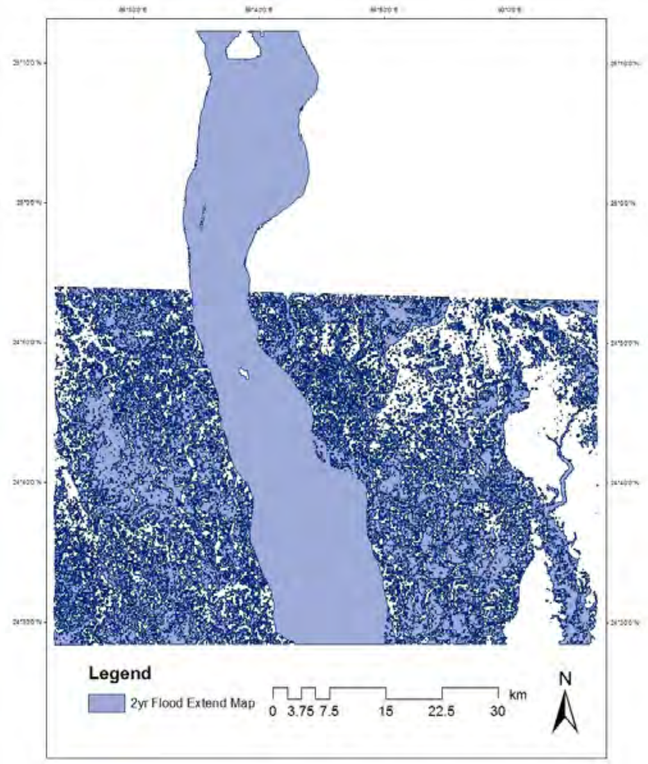


Figure 6.2: Map of extent of flood for 2-year return period

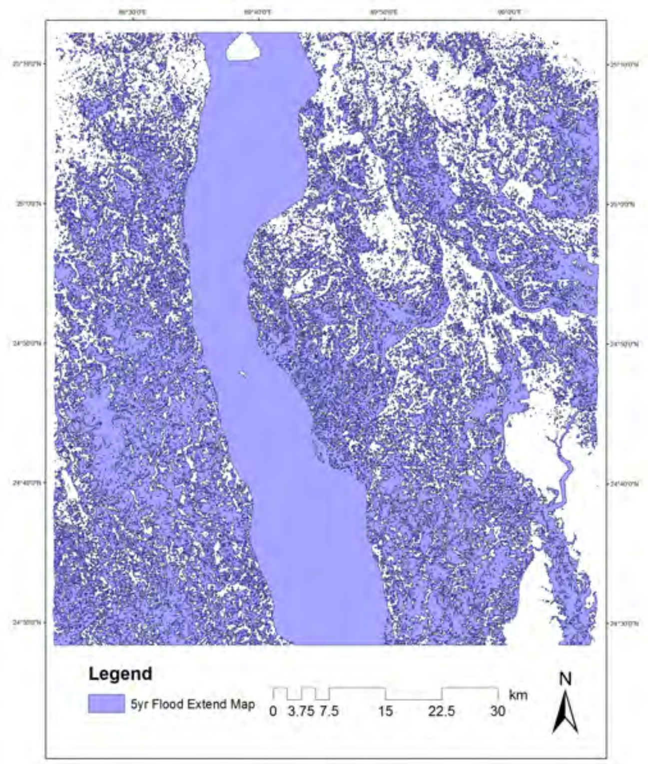


Figure 6.3: Map of extent of flood for 5-year return period

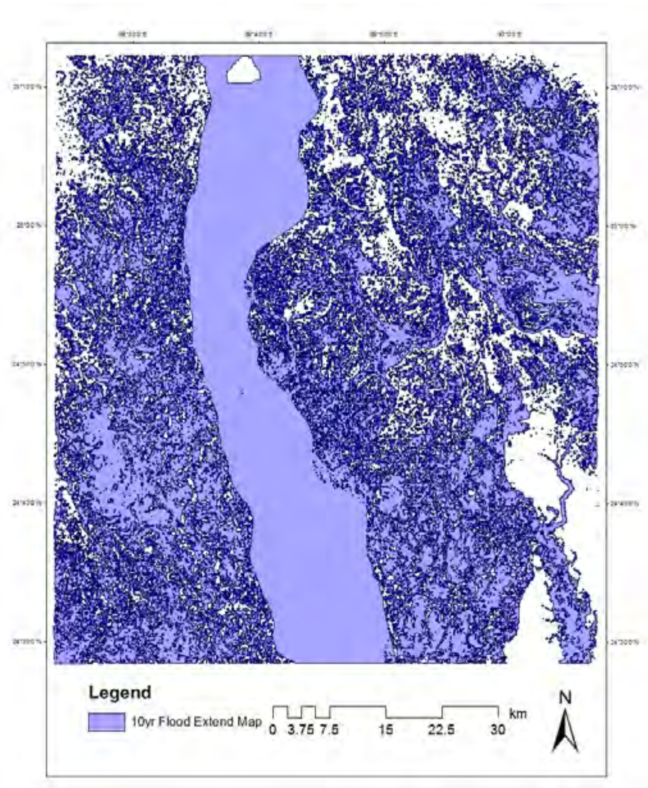


Figure 6.4: Map of extent of flood for 10-year return period

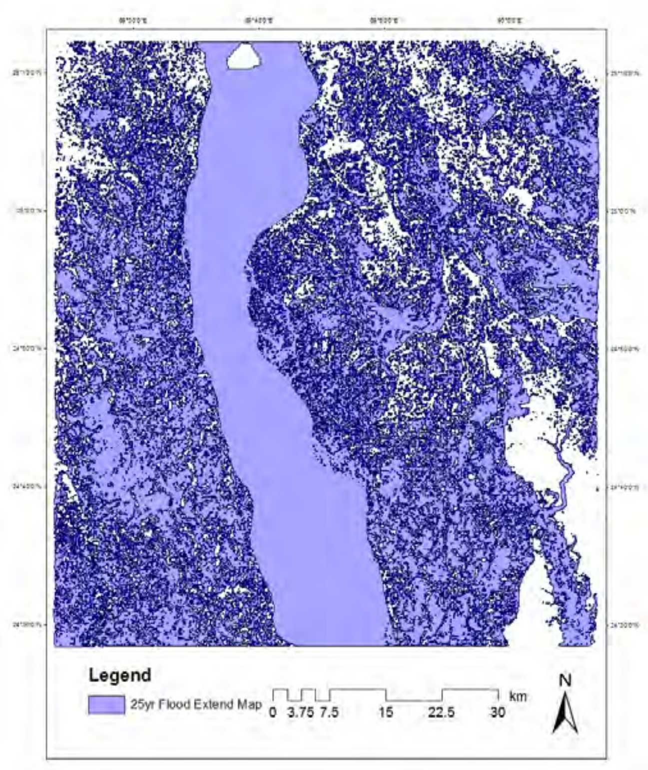


Figure 6.5: Map of extent of flood for 25-year return period

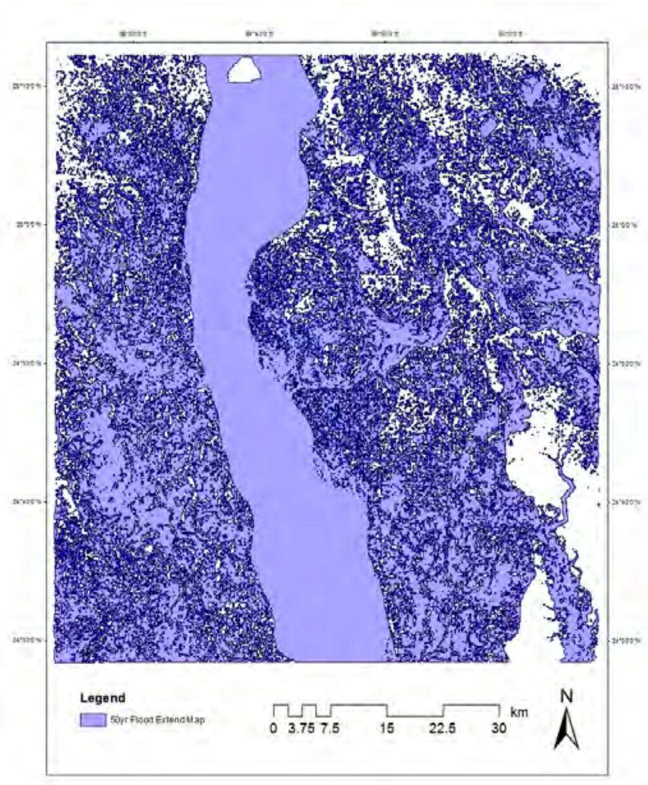


Figure 6.6: Map of extent of flood for 50-year return period

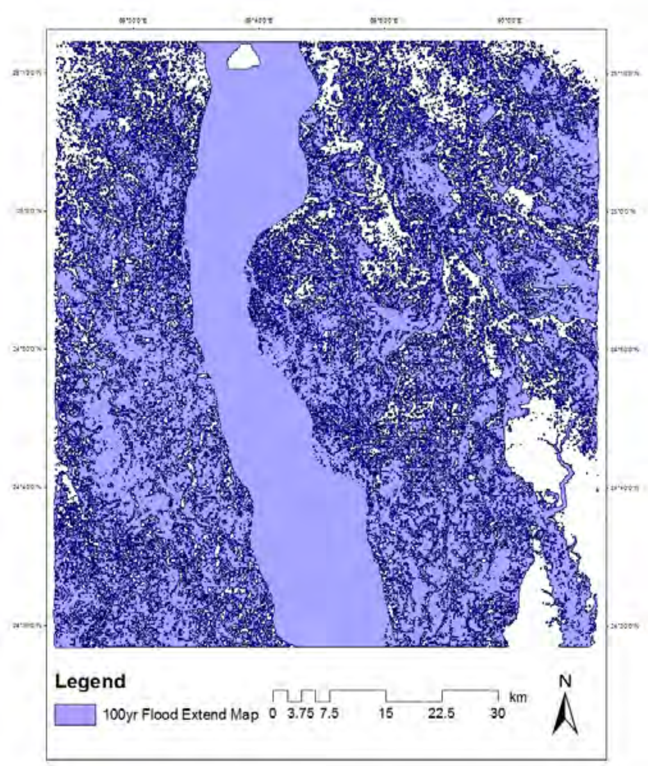


Figure 6.7: Map of extent of flood for 100-year return period

Table 6.3: Return periods and inundation area

Return Periods (year)	Inundation Area (sqkm)	Inundation area (%)
2	1852.19	26.12
5	2230.89	46.10
10	2474.44	51.14
25	2643.41	54.63
50	2752.97	56.89
100	2864.34	59.19

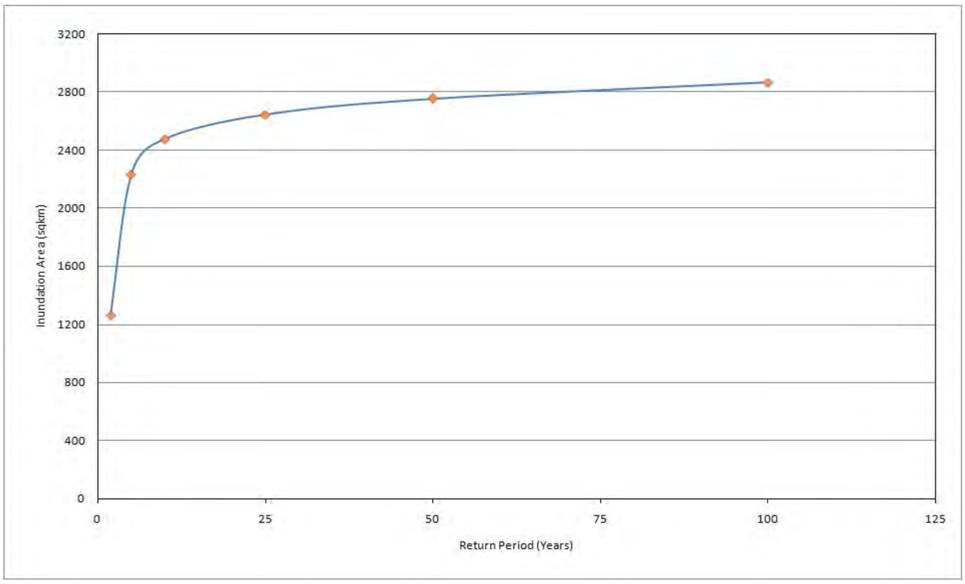


Figure 6.8: Return period and area inundation relationship

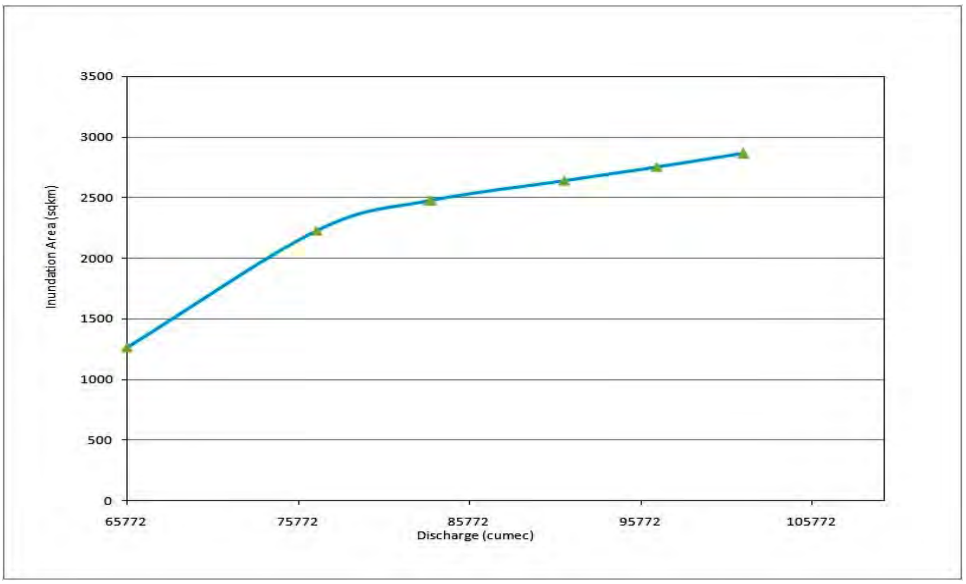


Figure 6.9: Discharge versus inundation area relationship

6.3.2 Flood inundation depth analysis

Flood inundation depth maps of the study area for 2-year, 5-year, 10-year, 25-year, 50-year and 100-year return period have been prepared by overlaying flood grid depths with the TIN (Fig: 6.10 to Fig: 6.15). In the study, inundated areas are defined into five qualitative inundation depth classes viz. Very High Land (0m - 0.3m), High Land (0.3m - 0.9m), Medium Land (0.9m - 1.2 m), Low Land (1.2m - 3.6m) and Very Low Land (> 3.0m) based on the inundation depth. The results of this assessment are summarized in Table 6.4 and Fig: 6.16. The classification of flood depth areas indicates that 33 to 42% of the total flooded area have been inundated by water depth between 1.2 to 3.6 m and 28 to 31% of the total flooded area have been inundated by water depth greater than 3 m. The total area under the water depth of 0.3 m is 6 to 15%.

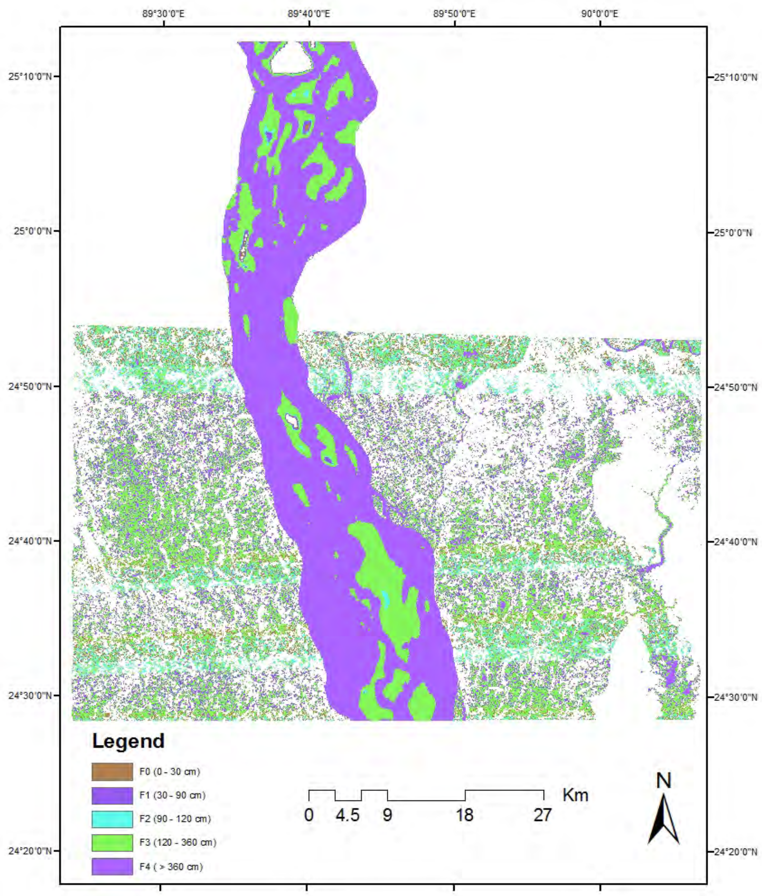


Figure 6.10: Flood inundation depth map for 2 years return period

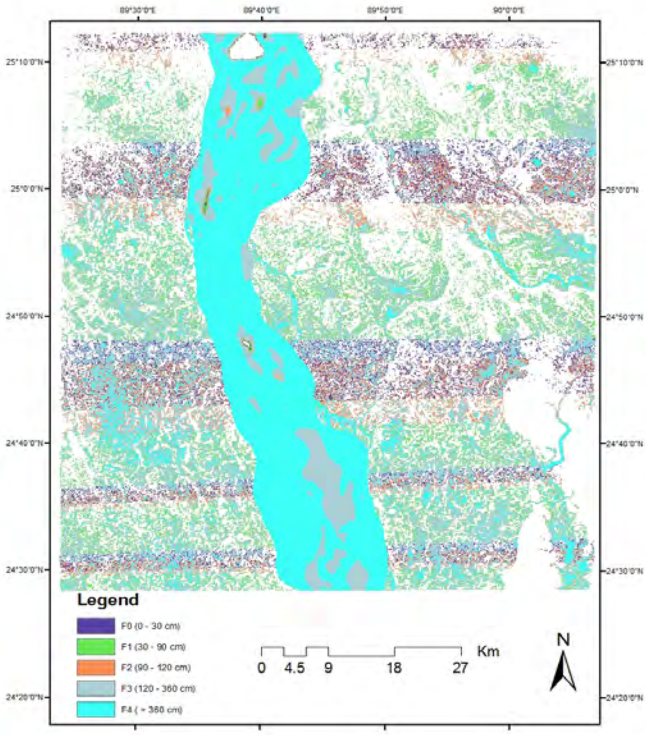


Figure 6.11: Flood inundation depth map for 5-year return period

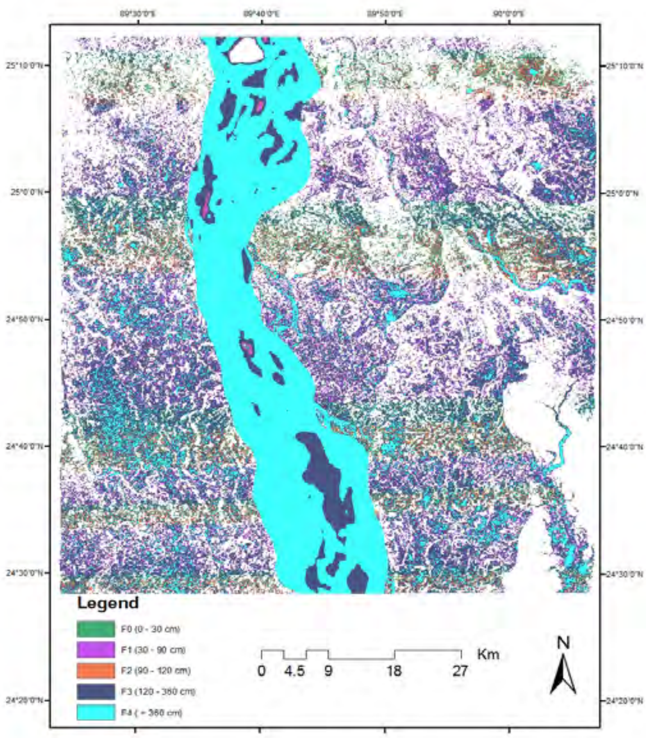


Figure 6.12: Flood inundation depth map for 10-year return period

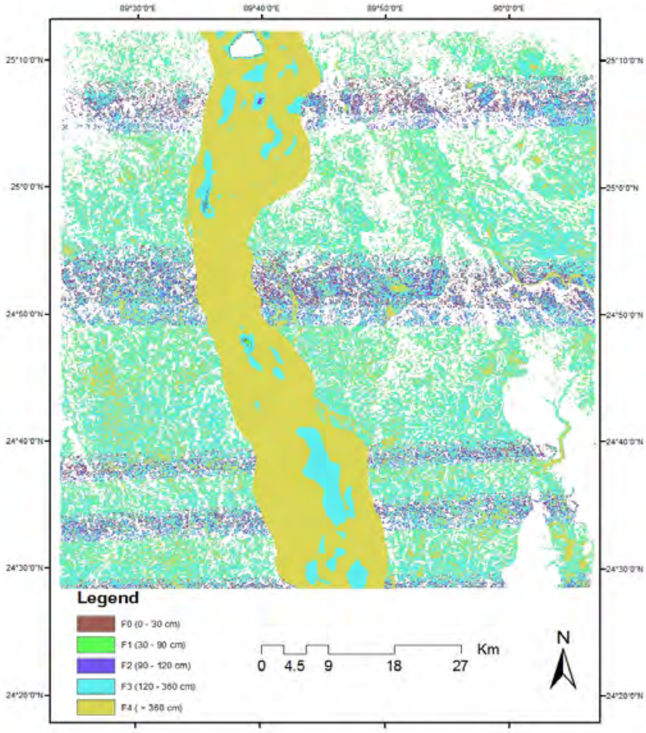


Figure 6.13: Flood inundation depth map for 25-year return period

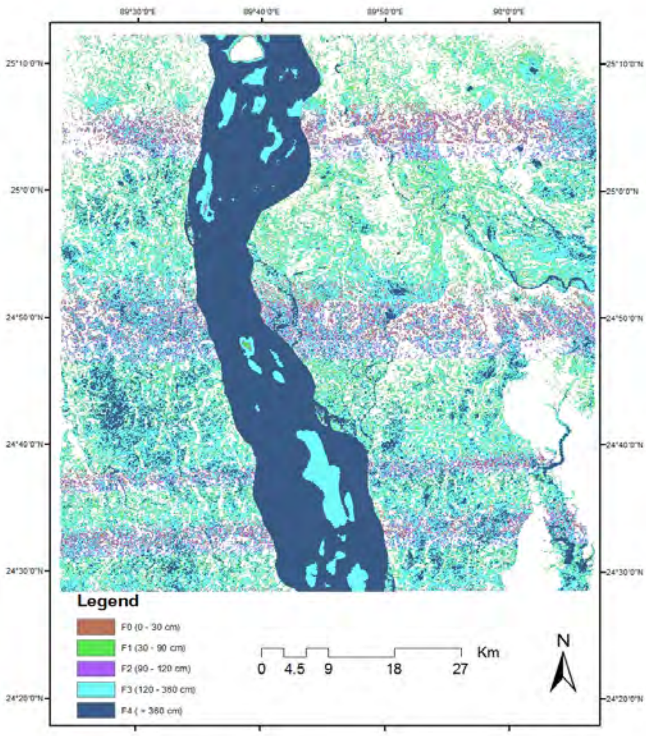


Figure 6.14: Flood inundation depth map for 50-year return period

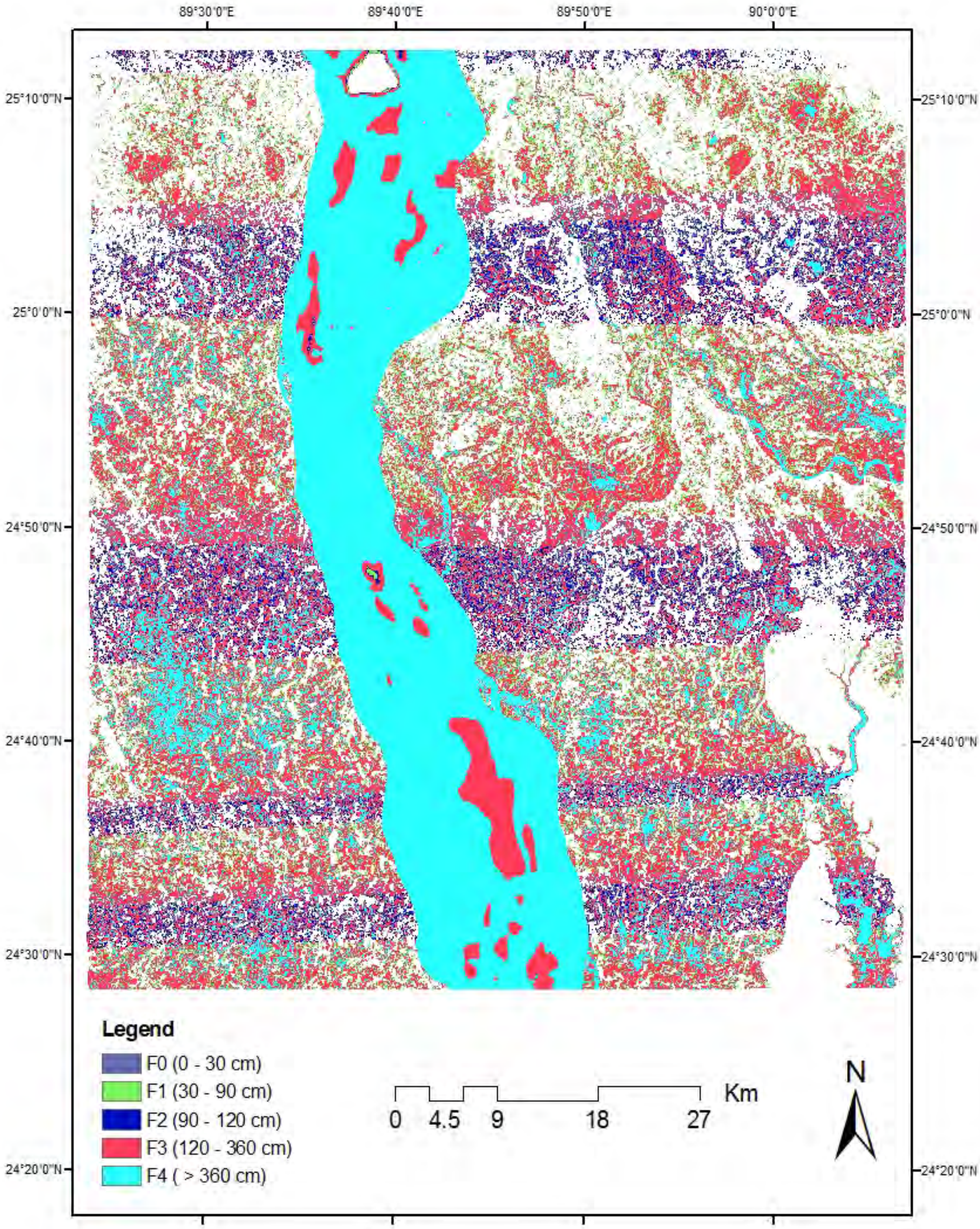


Figure 6.15: Flood inundation depth map for 100-year return period

Table 6.4: Calculation of flood area according to flood inundation depth categories

Return	Flood Types	F0	F1	F2	F3	F4	Total
Period	Water depth (cm)	0 - 30	30 - 90	90 - 120	120 - 360	> 360	
2-yr	Area (sqkm)	200.44	285.99	156.78	380.13	250.97	1274.31
	%	15.73	22.44	12.30	29.83	19.69	100
5-yr	Area (sqkm)	211.09	358.78	211.58	874.42	572.38	2228.25
	%	9.47	16.10	9.50	39.24	25.69	100
10-yr	Area (sqkm)	215.23	423.30	170.98	997.96	667.26	2474.73
	%	8.70	17.10	6.91	40.33	26.96	100
25-yr	Area (sqkm)	168.18	426.33	176.82	1069.06	773.68	2641.29
	%	6.37	16.14	6.69	41.50	29.30	100
50-yr	Area (sqkm)	169.88	414.73	185.03	1151.02	830.38	2751.06
	%	6.18	15.08	6.73	41.84	30.18	100
100-yr	Area (sqkm)	180.39	381.75	217.30	1203.82	883.90	2867.16
	%	6.29	13.31	7.58	41.99	30.83	100

The figure: 6.16 below shows that the total area inundated by water depth between 1.2 m to 3.6 m and more than 3.6 m increased considerably with the increase in the intensity of flooding. Total area under water depth of less than 0.9 m decreased slightly with the increase in the intensity of flooding.

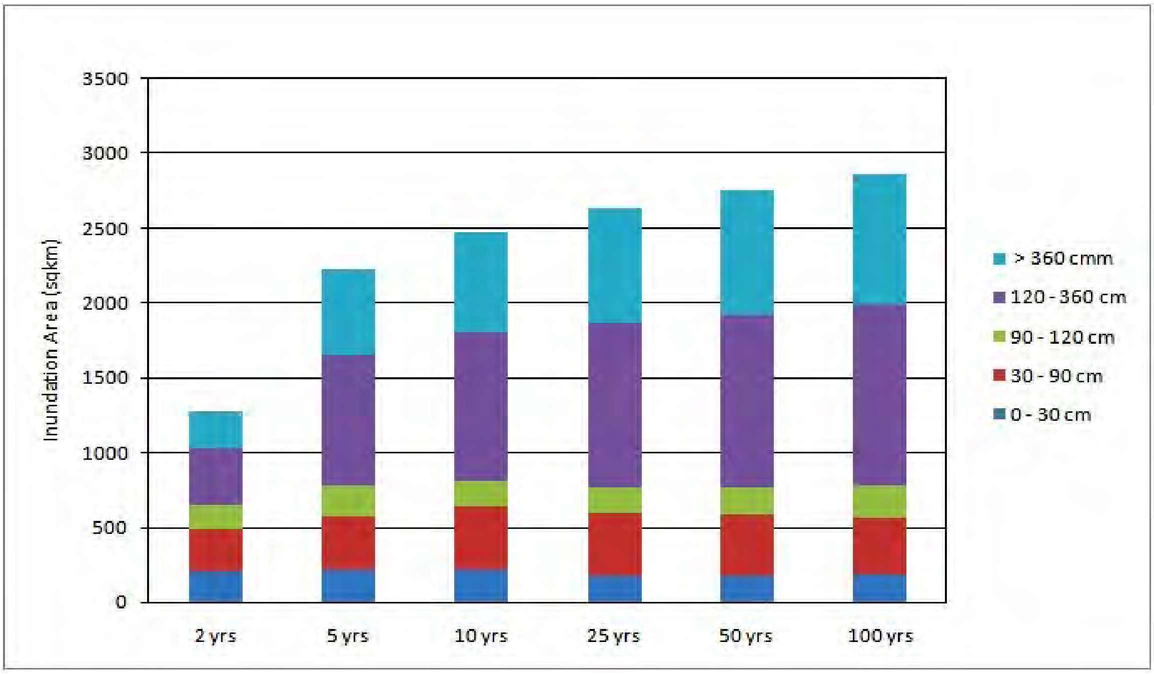


Figure 6.16: Return period-flood depth relationship

6.4 Unsteady flow analysis and flood mapping

Unsteady simulations are done for the year of 2001 to 2005. Boundary condition hydrographs for unsteady simulation are shown in figure: 6.17 and 6.18 .

Flood inundation area simulated by unsteady flow simulation for different years is shown in the figure 6.19, whereas danger water level has been considered as a levee elevation. Figure 6.19 shows, about 49% area was inundated in 2004 and about 31% area was inundated in 2003. For the other years, different percentage of area were inundated. Normally floods arose in the month of July and sometime it appeared earlier in August.

Table: 6.5 represents the flood area with five days interval from 15 June to 15 October for different years. The maximum 23.46 sqkm area was inundated on 10th July in 2004.

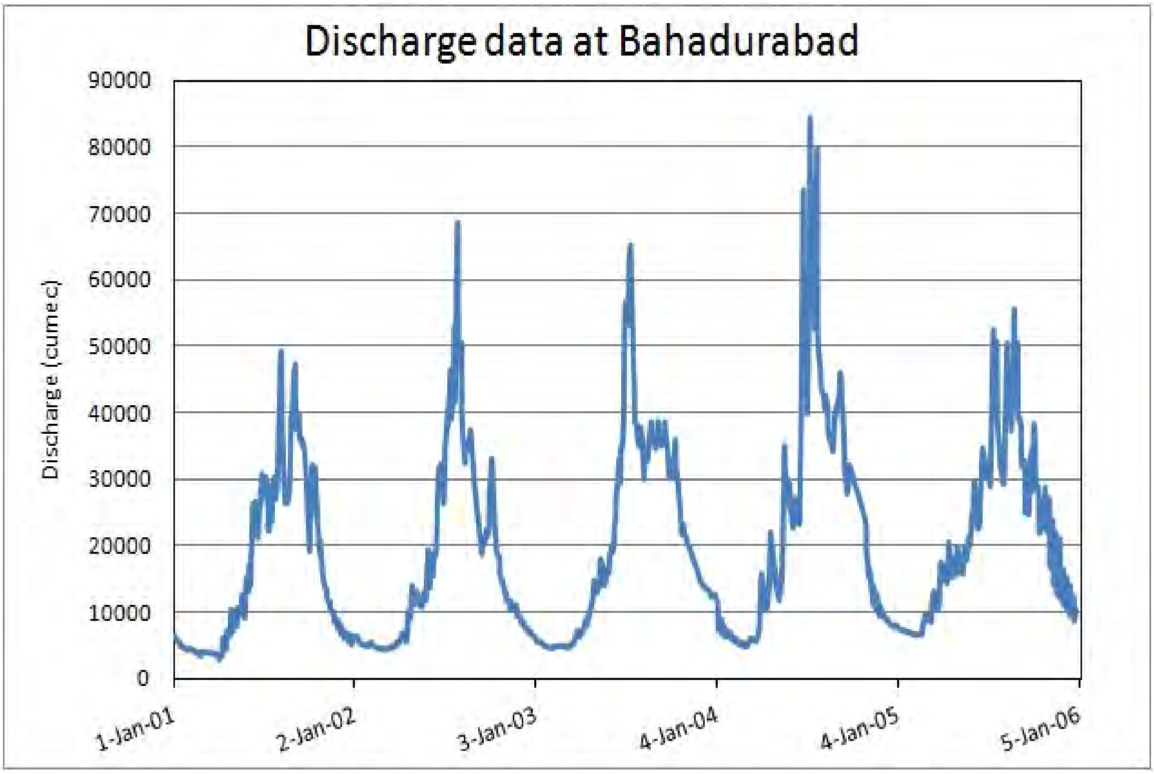


Figure 6.17: U/S Boundary discharge data at Bahadurabad station

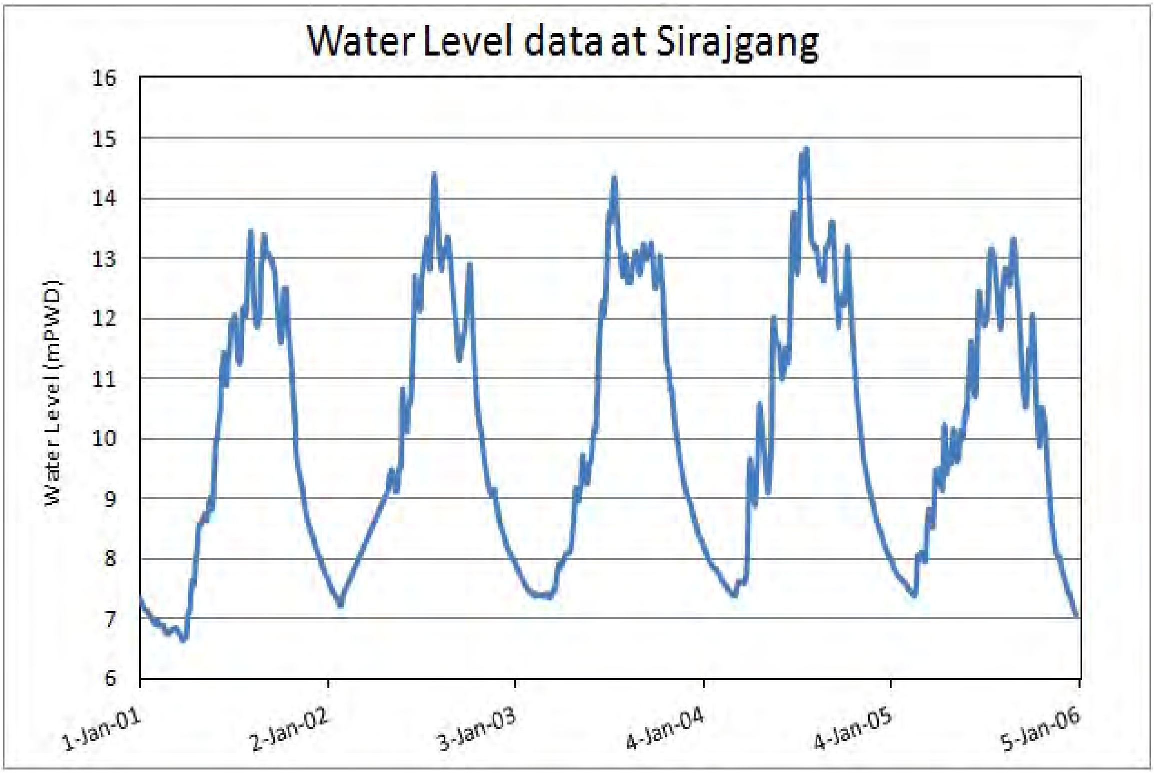


Figure 6.18: U/S Boundary discharge data at Sirajganj station

Table 6.5: Five days interval flood inundation area from 2001 to 2005

	Inundation Area (sqkm)				
Date	2001 yrs	2002 yrs	2003 yrs	2004 yrs	2005 yrs
15-Jun	31.93	0.00	104.26	0.00	0.00
20-Jun	0.00	203.43	220.88	65.12	66.60
25-Jun	103.04	202.59	294.62	1501.68	267.78
30-Jun	104.64	102.49	717.56	1135.08	220.58
5-Jul	161.80	469.86	1475.76	786.98	187.89
10-Jul	0.00	653.21	1455.53	2344.42	161.72
15-Jul	0.00	811.76	1437.24	2115.30	907.09
20-Jul	158.28	818.82	979.56	1586.86	917.06
25-Jul	101.78	1187.23	597.25	2288.44	690.36
30-Jul	312.11	1355.19	400.90	1207.55	238.29
5-Aug	1040.57	1008.00	508.91	829.30	159.43
10-Aug	219.25	381.60	203.20	732.52	558.12
15-Aug	69.32	403.26	238.71	562.15	656.88
20-Aug	102.57	425.40	478.49	437.08	828.35
25-Aug	517.57	516.24	543.77	336.67	824.94
30-Aug	883.51	203.54	419.23	665.24	993.04
5-Sep	593.57	46.74	483.95	771.44	707.57
10-Sep	621.87	0.00	546.48	954.03	511.35
15-Sep	478.25	0.00	434.74	672.61	203.55
20-Sep	368.92	0.00	575.10	187.63	64.38
25-Sep	162.52	0.00	462.33	132.01	132.55
30-Sep	0.00	0.00	221.54	218.59	236.82
5-Oct	0.00	238.76	203.33	174.19	239.05
10-Oct	162.32	45.84	330.30	179.77	186.96
15-Oct	115.94	0.00	202.03	131.48	119.25

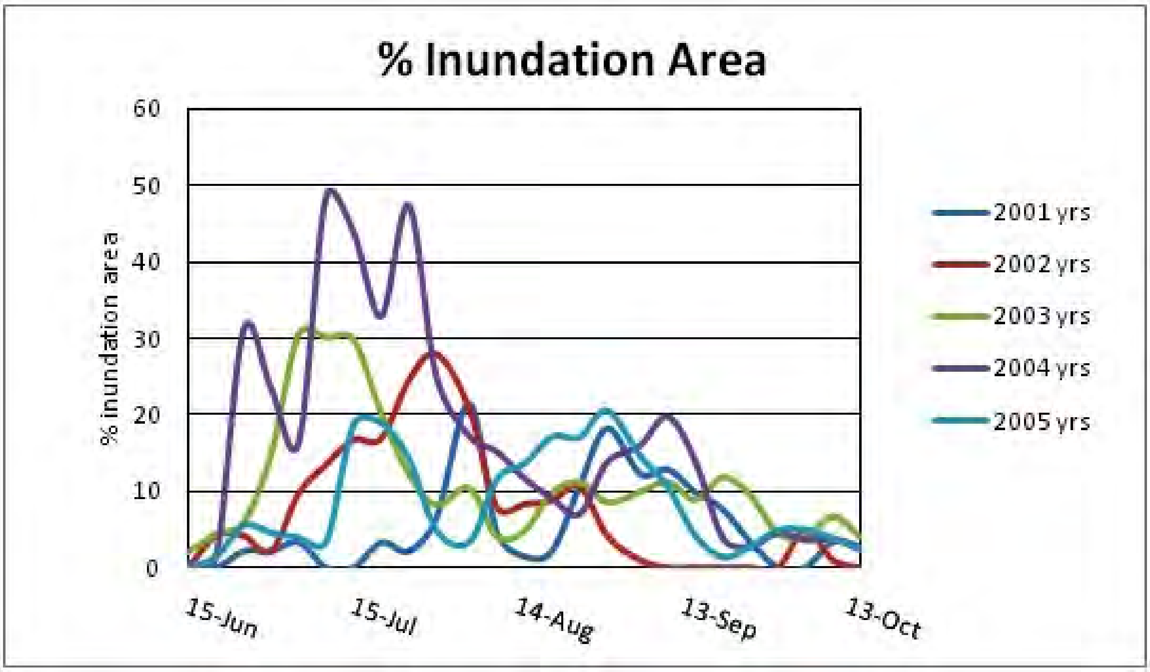


Figure 6.19: Inundation area for different years at danger water level levee

6.4.1 Relation between water level and inundation area

The relation between water level and inundation area is shown in figure 6.20. Water level at Kazipur gauge station corresponding to discharge are considered to determine the relationship between inundation area with water level. Up to 15.12 m water level the area is not inundated. The inundation area increases with the increase of water level after 15.12 m river water level. The increasing inundation area with respect to water level is followed by two degree polynomial equation $y = 4.77x^2 - 138.76x + 1008.30$. This equation is developed from five years unsteady simulation water level and its corresponding inundation area. About 49% area is inundated for the 17.77 m mean water level along the river reach.

6.4.2 Effect of levee height on flood inundation area

The rise of a river water level to an elevation such that the river overflows its levee or banks causing damage. The levee elevation play important role in controlling the floodplain area. The relation between levee elevation and inundation area is shown in 6.21. Along the river bank, levee elevation 0.3 m (1 ft), 0.91 m (3 ft), 1.52 m (5 ft), 2.13 m (7 ft) and 2.56 m (8.4 ft) have been raised from existent levee elevation and

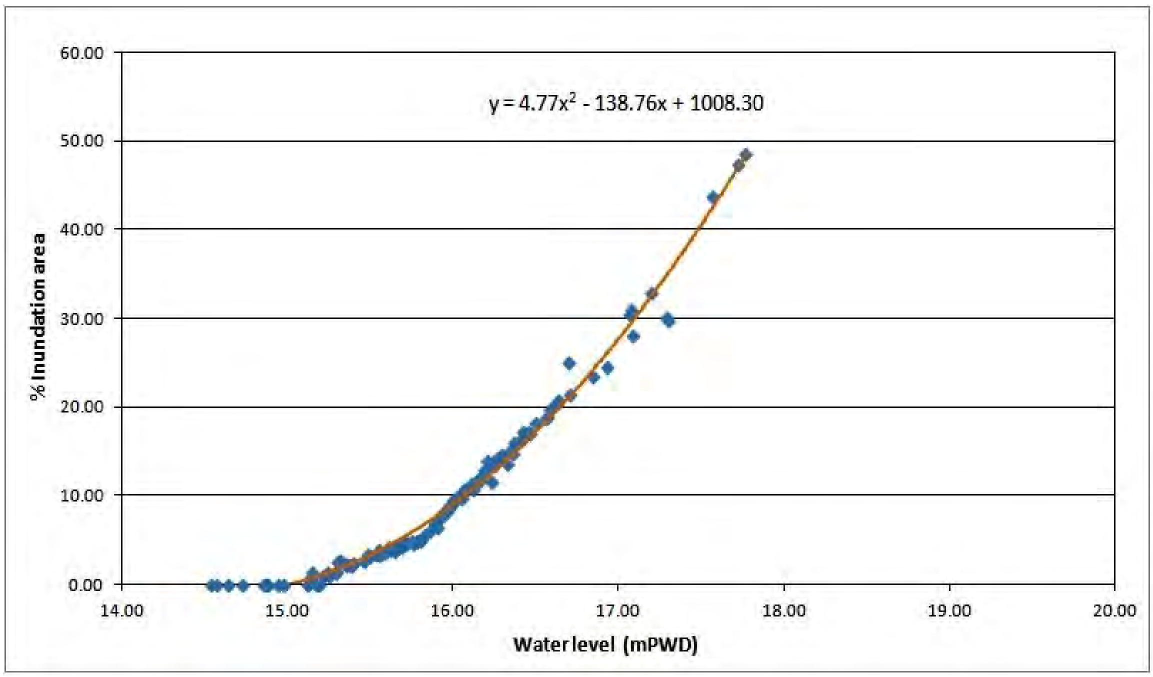


Figure 6.20: Water level vs % inundation area relationship at Kazipur station

simulations have been performed to assess the impact levee height on flood inundation. At maximum levee elevation of 2.56 m the floodplain is not inundated. The river downstream levee elevation is lower than the upstream levee elevation. So downstream levee elevation should be raised more than upstream to protect flood inundation. As shown in figure 6.21, the flood inundation area decreases with increase the levee elevation. Impact of the levee height on flood inundation for 2, 5 and 10 year return periods in higher than 25, 50 and 100 year return periods. If the levee elevation is raised up to 0.91 m, there is no impact on flood inundation for 100 year return period flood. The flood inundation area is decreased, if the levee elevation raised greater than 0.91 m for 100 year return period.

6.5 Effect of climate change on flood inundation

Frequency analysis of peak discharges does not consider the effect of climate change explicitly. In order to study effect of climate change, sensitivity analysis of different percentage of increases of discharges are studied. Paul *et al.* (2015) found that discharge in the Jamuna River can be increased up to 4 to 13 % by the 2080s. Considering that effect of 5%, 10%, 15% and 20% of 100 year maximum discharge on flood inundation

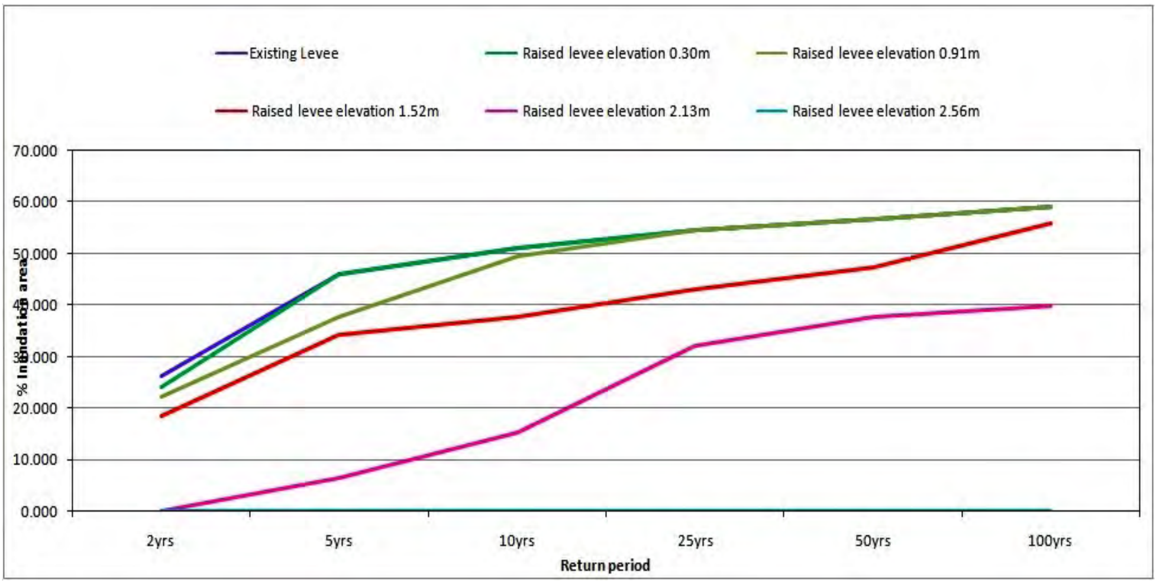


Figure 6.21: Impact of levee height on flood inundation area

is simulated. The numerical simulation shows that with an increase of 20% discharge inundation area can increase up to 67.15% (figure: 6.22).

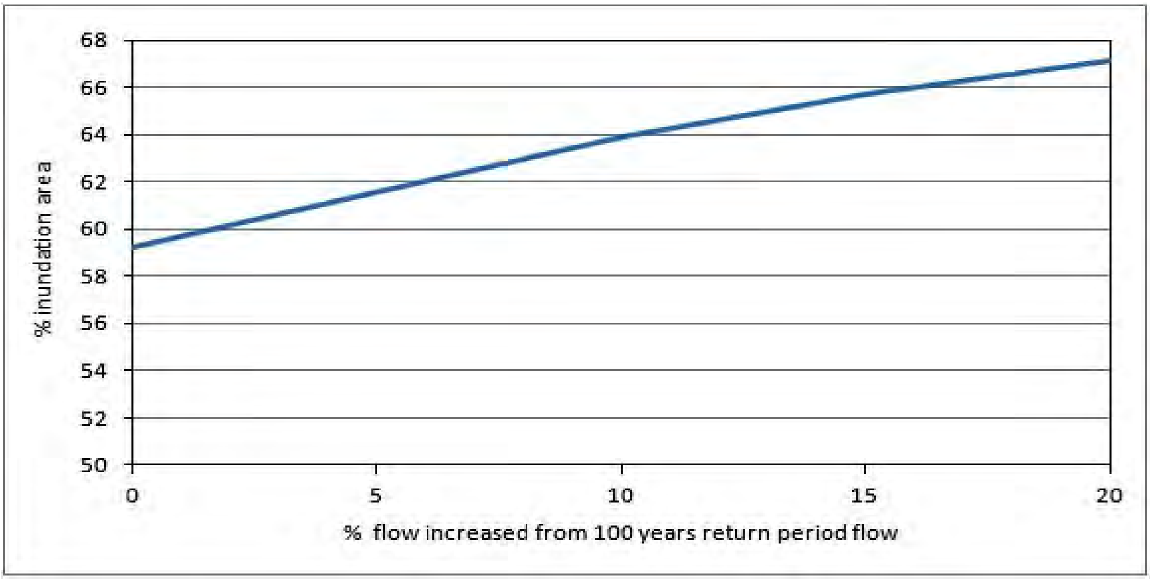


Figure 6.22: Effect of climate change on flood inundation

6.6 Discussion

The applications of hydraulic model and GIS for floodplain analysis and risk mapping have been limited in Bangladesh. The situation of river flooding in Bangladesh is completely different from others countries, as the rivers are more unstable and river bank erosion is a regular phenomenon. There are very few flood control structures like spurs and dikes and the river banks and boundary lines are not clearly defined. Hence, the floodplain analysis and modeling are subjected to a number of new sets of constraints. This study presents an approach of conducting a similar study, within these constraints.

- HEC-RAS and ArcView GIS were the primary software packages used for this analysis. HEC-GeoRAS extension facilitated the exchange of data between ArcView GIS and HEC-RAS.
- The topographic elevations and river bathemetric data are used to prepare the digital terrain model of the study area, so that it can represent the river channel and floodplains adequately.
- The flood discharge of different return periods have been derived by different frequency analysis method. Among the methods, the best fitted one with observed data has been taken as flood discharge for the analysis.
- During the simulation in HEC-RAS, several issues were carefully considered. In HEC-RAS, water passes through the river bank without any obstruction, if no levee is considered. So levee selection is very crucial.
- According to the model results, there is considerable flooding in the area even at flood discharge of 5-year flood. This implies that the channel capacity is small to carry the flood water discharge and the levee and its elevation are not adequate.
- The flood inundation depth map prepared indicate 30.41% area with water depth greater than 3.6 meter for 100-year return period of the study area.

6.7 Applications

The methodology described in this study offers several practical applications; some derived from the fact of using an automated floodplain modeling process and some associated with the resulting floodplain maps. Floodplain evaluations are of substantial interests to planners, land developers, design engineers and general public alike. This can also provide the basis for floodplain management programs. The following are some of the potential applications.

- **Design of flood control structures:** Floodplain modeling can be used to determine suitability of building flood control structures for prevention purposes (i.e. embankment, detention ponds).

- **Non-structural measure to risk reduction strategy:** This study can provide the basis for the planning of non-structural measures for flood protection. Measures like floodplain zoning, demarcation of the river boundary lines can be planned based on the findings of this study. This can also help in the planning of the evacuation and relief routes and storing of the emergency flood relief materials and equipments.

Chapter 7

Conclusion and Recommendation

7.1 Conclusion

This study presents a systematic approach in the preparation of flood inundation and flood hazard maps with the application of hydrodynamic models and GIS. The change of flooding with time also shows in this study by performing unsteady flow analysis and flood mapping. The major tools used in this method are a one-dimensional numerical model HEC-RAS and ArcView GIS for spatial data processing and HEC-GeoRAS for interfacing between HEC-RAS and ArcView GIS.

- There is an increasing trend of discharge at Bahadurabad gauge station of the Jamuna river. Flood frequency analysis is considered to assess different return periods future maximum discharge for flood extend and inundation depth maps.
- Among the five distributions, the Log Normal Distribution (LN) is the best distribution for flood frequency analysis in this station. It is observed that flood frequency analysis by Log Normal (LN) discharges of 65772, 76871, 8519, 91299, 96703, and 101790 m^3/sec for 2, 5, 10, 25, 50, and 100 year return periods respectively.
- The flood inundation area increase with the increase of return period. It followed into the log curve $y = 249.84ln(x) + 1789.3$. For 2, 5, 10, 25, 50 and 100 year return periods 26.12%, 46.10%, 51.14%, 54.63%, 56.89% and 59.19% of the area were found to be inundated, respectively.

- In the 100-year return period 59.19 % land become inundated. The F0, F1, F2, F3 and F4 types land inundated area are 6.29, 13.31, 7.58, 41.99 and 30.83 % of 59.19 % respectively.

- The relation between water level and inundation area is followed by the two degree polynomial equation $y = 4.77x^2 - 138.76x + 1008.30$. It is seen from unsteady simulation of flow, the 49% area was inundated on 10 july, 2004.

- It has been found that, if levee elevation is raised up to 2.56 m from the existent levee elevation, then no land area will be inundated. For the 100 year return period, if levee elevation raised up to 2.13 m from existent levee elevation, then flood inundation land area decreased from 59.19% to 40%.

- This method of floodplain mapping can be used as a useful tool for floodplain management and for decision making as well for future development within the floodplain of the Jamuna river basin.

7.2 Recommendation

Based on the aforementioned result and the experience gained during the study, the following recommendations are made.

- A simple study about climate change impact on flood inundation is done in this study. However, for more accurate prediction, future discharge from a hydrologic model can be used in future studies.

- Only the impact of levee on flood has been done in this study. Effect of other flood control measures such as, flood control dam, reservoir, channelization, flood diversion etc can be studied in future studies.

- Current HEC-RAS uses 1D model with flood plain. However, it does not have 1D/2D coupled model. For future studies, a 1D/2D (such as SOBEK, HEC-RAS(1D/2D)) coupled model can be used to see the differences between this two models.

- In this study levees are assumed as non-breachable. However, levee breaching can be occurred which can be studied in future studies.

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Appendix A

Hydrological data

A.1 Discharge data at Bahadurabad station

Date	Discharge	Date	Discharge	Date	Discharge	Date	Discharge
1/1/05	7672.18	1/19/05	7111.99	2/6/05	6620.04	2/24/05	8057.9
1/2/05	7882.65	1/20/05	7072.28	2/7/05	6590.4	2/25/05	8295.56
1/3/05	7723.93	1/21/05	7032.69	2/8/05	6554.63	2/26/05	8398.17
1/4/05	7668.5	1/22/05	7004.09	2/9/05	6539.81	2/27/05	8290.71
1/5/05	7609.5	1/23/05	6975.56	2/10/05	6535.45	2/28/05	9577.61
1/6/05	7531.54	1/24/05	6936.28	2/11/05	6552.02	3/1/05	8878.97
1/7/05	7524.32	1/25/05	6883.8	2/12/05	6552.9	3/2/05	9679.95
1/8/05	7418.52	1/26/05	6844.74	2/13/05	6538.08	3/3/05	9090.08
1/9/05	7377.95	1/27/05	6873.04	2/14/05	6533.73	3/4/05	9817.05
1/10/05	7289.08	1/28/05	6915.4	2/15/05	6518.94	3/5/05	9075.28
1/11/05	7277.56	1/29/05	6953.98	2/16/05	6504.16	3/6/05	9552.11
1/12/05	7222.59	1/30/05	6838.04	2/17/05	6520.68	3/7/05	8790.36
1/13/05	7211.08	1/31/05	6830.09	2/18/05	6537.23	3/8/05	9264.93
1/14/05	7183.48	2/1/05	6726.03	2/19/05	6569.52	3/9/05	8687.16
1/15/05	7144.93	2/2/05	6760.62	2/20/05	6445.21	3/10/05	9223
1/16/05	7122.15	2/3/05	6725.32	2/21/05	6602.38	3/11/05	8656.31
1/17/05	7133.94	2/4/05	6674.24	2/22/05	6890.35	3/12/05	9239.8
1/18/05	7093.23	2/5/05	6644.47	2/23/05	7424.97	3/13/05	8522.3

Date	Discharge	Date	Discharge	Date	Discharge	Date	Discharge
3/14/05	11552.25	4/12/05	14830.12	5/11/05	17157.7	6/9/05	28943.13
3/15/05	10520.33	4/13/05	15401.51	5/12/05	15857.92	6/10/05	27556.03
3/16/05	12628.01	4/14/05	14265.23	5/13/05	17244.3	6/11/05	26338.65
3/17/05	10879.15	4/15/05	15703.04	5/14/05	15999.18	6/12/05	25626.49
3/18/05	13098.76	4/16/05	16189.94	5/15/05	17331.16	6/13/05	23891.54
3/19/05	11372.25	4/17/05	20399.32	5/16/05	15661.59	6/14/05	23523.4
3/20/05	12934.69	4/18/05	18819.85	5/17/05	17889.31	6/15/05	22706.33
3/21/05	10849.88	4/19/05	19971.05	5/18/05	17912.03	6/16/05	22429.88
3/22/05	12230.23	4/20/05	17303.16	5/19/05	19833.01	6/17/05	22552.81
3/23/05	10535.56	4/21/05	17745.88	5/20/05	18062.19	6/18/05	23004.7
3/24/05	11865.58	4/22/05	15670.2	5/21/05	19025.04	6/19/05	24215.96
3/25/05	10290.75	4/23/05	16195.86	5/22/05	17729.5	6/20/05	26579.15
3/26/05	11698.85	4/24/05	15233.19	5/23/05	19376.09	6/21/05	28420.84
3/27/05	10287.56	4/25/05	17724.23	5/24/05	17843.61	6/22/05	30399.97
3/28/05	12733.31	4/26/05	16886.93	5/25/05	19364.88	6/23/05	32762.03
3/29/05	11117.35	4/27/05	17965.72	5/26/05	18782.46	6/24/05	34318.88
3/30/05	14940	4/28/05	15999.61	5/27/05	21006.3	6/25/05	34610.9
3/31/05	15602.03	4/29/05	17049.71	5/28/05	20717.55	6/26/05	32972.57
4/1/05	17461.59	4/30/05	15654.55	5/29/05	21399.02	6/27/05	34084.38
4/2/05	15855.96	5/1/05	17320.23	5/30/05	20028.03	6/28/05	33161.66
4/3/05	16353.99	5/2/05	16437.88	5/31/05	20994.44	6/29/05	32939.57
4/4/05	14532.36	5/3/05	18553.97	6/1/05	21660.62	6/30/05	32760.4
4/5/05	15859.41	5/4/05	18581.74	6/2/05	22722.74	7/1/05	31839.18
4/6/05	14902.49	5/5/05	19856.09	6/3/05	24264.64	7/2/05	30749.63
4/7/05	16802.41	5/6/05	18066.28	6/4/05	24744.05	7/3/05	30288.04
4/8/05	15750.21	5/7/05	18811.29	6/5/05	24874	7/4/05	31863.32
4/9/05	16899.08	5/8/05	16877.51	6/6/05	25321.96	7/5/05	31668.15
4/10/05	15434.55	5/9/05	17734.88	6/7/05	28144.41	7/6/05	31459.54
4/11/05	16027.42	5/10/05	15989.72	6/8/05	29650.22	7/7/05	31265.38

Date	Discharge	Date	Discharge	Date	Discharge	Date	Discharge
7/8/05	30823.61	8/6/05	29351.59	9/4/05	50585.18	10/3/05	28362.14
7/9/05	30097.87	8/7/05	29273.07	9/5/05	39193.33	10/4/05	30030.68
7/10/05	29015.77	8/8/05	32088.94	9/6/05	39207.32	10/5/05	33572.25
7/11/05	32017	8/9/05	36298.81	9/7/05	38826.52	10/6/05	37104.83
7/12/05	35239.6	8/10/05	39357.34	9/8/05	38991.63	10/7/05	38375.66
7/13/05	38523.69	8/11/05	42078.89	9/9/05	38808.63	10/8/05	37461.71
7/14/05	41448.98	8/12/05	45195.84	9/10/05	38429.78	10/9/05	36719.06
7/15/05	47030.59	8/13/05	47957.74	9/11/05	38262.43	10/10/05	30180.79
7/16/05	50045.87	8/14/05	50196.54	9/12/05	31891.4	10/11/05	29734.87
7/17/05	52349.24	8/15/05	39497.51	9/13/05	32327.01	10/12/05	29250.73
7/18/05	43492.71	8/16/05	41185.66	9/14/05	32062.82	10/13/05	28998.2
7/19/05	44504.57	8/17/05	42761	9/15/05	32149	10/14/05	28425.84
7/20/05	46125.01	8/18/05	43326.9	9/16/05	32276.82	10/15/05	28574.73
7/21/05	47967.27	8/19/05	43768.41	9/17/05	32124.41	10/16/05	28790.97
7/22/05	49136.88	8/20/05	45077.01	9/18/05	32674.22	10/17/05	21847.54
7/23/05	49931.64	8/21/05	46564.46	9/19/05	25067.96	10/18/05	21963.51
7/24/05	50630.28	8/22/05	37537.18	9/20/05	25790.89	10/19/05	22163.69
7/25/05	38814.3	8/23/05	39624.8	9/21/05	26937.26	10/20/05	22388.71
7/26/05	37528.71	8/24/05	41323.07	9/22/05	27484.45	10/21/05	23125.96
7/27/05	36275.5	8/25/05	44497.59	9/23/05	28354.36	10/22/05	24960.7
7/28/05	35345.05	8/26/05	48179.84	9/24/05	29654.08	10/23/05	26631.92
7/29/05	34165.96	8/27/05	51657.88	9/25/05	31267.9	10/24/05	23460.01
7/30/05	32932.33	8/28/05	55340.55	9/26/05	24828.51	10/25/05	24917.03
7/31/05	31592.35	8/29/05	44240.47	9/27/05	26767.29	10/26/05	25500.15
8/1/05	32902.43	8/30/05	46518.88	9/28/05	29639.75	10/27/05	26294.79
8/2/05	31921.77	8/31/05	48197.24	9/29/05	32447.07	10/28/05	27021.13
8/3/05	30678.23	9/1/05	49515.03	9/30/05	33658.72	10/29/05	27927.17
8/4/05	29928.92	9/2/05	50240.24	10/1/05	33795.09	10/30/05	28645.01
8/5/05	29430.07	9/3/05	50598.29	10/2/05	34003.52	10/31/05	22255.3

Date	Discharge	Date	Discharge	Date	Discharge
11/1/05	22671.9	11/30/05	12649.28	12/29/05	9526.36
11/2/05	23189.21	12/1/05	13316.76	12/30/05	9937.3
11/3/05	23859.86	12/2/05	13978.41	12/31/05	10337.79
11/4/05	24513.35	12/3/05	14663.34		
11/5/05	25313.57	12/4/05	15392.68		
11/6/05	26034.34	12/5/05	16231.55		
11/7/05	26971.49	12/6/05	11050.52		
11/8/05	16856.33	12/7/05	11656.96		
11/9/05	17990.22	12/8/05	12342.74		
11/10/05	19064.42	12/9/05	13034.88		
11/11/05	20151.81	12/10/05	13712.87		
11/12/05	21323.48	12/11/05	14445.21		
11/13/05	22461.71	12/12/05	15152.03		
11/14/05	23673.52	12/13/05	10172.08		
11/15/05	14301.12	12/14/05	10736.95		
11/16/05	15388.44	12/15/05	11332.56		
11/17/05	16518.95	12/16/05	11950.63		
11/18/05	17780.9	12/17/05	12601.19		
11/19/05	18979.24	12/18/05	13256.14		
11/20/05	20255.79	12/19/05	13924.67		
11/21/05	21625.79	12/20/05	9408.07		
11/22/05	12675.72	12/21/05	9888.52		
11/23/05	13945.25	12/22/05	10361.18		
11/24/05	15264.22	12/23/05	10851.82		
11/25/05	16685.24	12/24/05	11379.16		
11/26/05	18157.87	12/25/05	11898.14		
11/27/05	19544.27	12/26/05	12398.2		
11/28/05	20796.43	12/27/05	8668.78		
11/29/05	12014.65	12/28/05	9080.92		

A.2 Water level data at Sirajganj station

Date	WL	Date	WL	Date	WL	Date	WL
1/1/05	8.04	01/19/05	7.7	02/06/05	7.49	2/24/05	7.81
1/2/05	8.02	01/20/05	7.69	02/07/05	7.48	2/25/05	8
1/3/05	8	01/21/05	7.68	02/08/05	7.47	2/26/05	8.05
1/4/05	7.99	01/22/05	7.67	02/09/05	7.46	2/27/05	8.05
1/5/05	7.97	01/23/05	7.65	02/10/05	7.46	2/28/05	8.02
1/6/05	7.94	01/24/05	7.65	02/11/05	7.45	3/1/05	8
1/7/05	7.91	01/25/05	7.64	02/12/05	7.44	3/2/05	7.99
1/8/05	7.88	01/26/05	7.64	02/13/05	7.43	3/3/05	8.01
1/9/05	7.86	01/27/05	7.63	02/14/05	7.42	3/4/05	8.09
1/10/05	7.83	01/28/05	7.6	02/15/05	7.4	3/5/05	8.1
1/11/05	7.81	01/29/05	7.59	02/16/05	7.4	3/6/05	8.09
1/12/05	7.8	01/30/05	7.59	02/17/05	7.38	3/7/05	8.05
1/13/05	7.79	01/31/05	7.59	02/18/05	7.38	3/8/05	8.02
1/14/05	7.76	02/01/05	7.58	02/19/05	7.37	3/9/05	7.99
1/15/05	7.75	02/02/05	7.58	02/20/05	7.39	3/10/05	7.97
1/16/05	7.73	02/03/05	7.56	02/21/05	7.41	3/11/05	7.94
1/17/05	7.72	02/04/05	7.55	02/22/05	7.47	3/12/05	7.94
1/18/05	7.7	02/05/05	7.51	02/23/05	7.62	3/13/05	8.02

Date	WL	Date	WL	Date	WL	Date	WL
3/14/05	8.27	4/12/05	9.3	5/11/05	9.75	6/9/05	11.6
3/15/05	8.52	4/13/05	9.22	5/12/05	9.67	6/10/05	11.47
3/16/05	8.64	4/14/05	9.17	5/13/05	9.6	6/11/05	11.22
3/17/05	8.68	4/15/05	9.13	5/14/05	9.62	6/12/05	11
3/18/05	8.78	4/16/05	9.36	5/15/05	9.66	6/13/05	10.9
3/19/05	8.81	4/17/05	9.91	5/16/05	9.66	6/14/05	10.8
3/20/05	8.81	4/18/05	10.22	5/17/05	9.74	6/15/05	10.77
3/21/05	8.76	4/19/05	10.22	5/18/05	9.92	6/16/05	10.7
3/22/05	8.68	4/20/05	10.07	5/19/05	10.08	6/17/05	10.68
3/23/05	8.62	4/21/05	9.75	5/20/05	10.13	6/18/05	10.7
3/24/05	8.56	4/22/05	9.58	5/21/05	10.08	6/19/05	10.83
3/25/05	8.54	4/23/05	9.45	5/22/05	10	6/20/05	11.12
3/26/05	8.5	4/24/05	9.41	5/23/05	9.98	6/21/05	11.44
3/27/05	8.5	4/25/05	9.54	5/24/05	10	6/22/05	11.75
3/28/05	8.58	4/26/05	9.79	5/25/05	10.06	6/23/05	12.05
3/29/05	8.71	4/27/05	9.76	5/26/05	10.1	6/24/05	12.36
3/30/05	8.99	4/28/05	9.72	5/27/05	10.24	6/25/05	12.43
3/31/05	9.33	4/29/05	9.62	5/28/05	10.41	6/26/05	12.38
4/1/05	9.45	4/30/05	9.56	5/29/05	10.45	6/27/05	12.26
4/2/05	9.46	5/1/05	9.57	5/30/05	10.45	6/28/05	12.15
4/3/05	9.38	5/2/05	9.61	5/31/05	10.4	6/29/05	12.11
4/4/05	9.28	5/3/05	9.72	6/1/05	10.36	6/30/05	12.11
4/5/05	9.21	5/4/05	9.95	6/2/05	10.56	7/1/05	12.09
4/6/05	9.25	5/5/05	10.11	6/3/05	10.72	7/2/05	11.99
4/7/05	9.36	5/6/05	10.15	6/4/05	10.93	7/3/05	11.95
4/8/05	9.45	5/7/05	10.1	6/5/05	10.96	7/4/05	11.86
4/9/05	9.48	5/8/05	10.03	6/6/05	11	7/5/05	11.86
4/10/05	9.44	5/9/05	9.95	6/7/05	11.27	7/6/05	11.88
4/11/05	9.38	5/10/05	9.82	6/8/05	11.55	7/7/05	11.93

Date	Wl	Date	WL	Date	WL	Date	WL
7/8/05	11.96	8/6/05	11.81	9/4/05	12.99	10/3/05	11.28
7/9/05	11.99	8/7/05	11.86	9/5/05	12.78	10/4/05	11.34
7/10/05	11.96	8/8/05	11.91	9/6/05	12.67	10/5/05	11.59
7/11/05	12.02	8/9/05	12.24	9/7/05	12.54	10/6/05	11.96
7/12/05	12.2	8/10/05	12.45	9/8/05	12.44	10/7/05	12.05
7/13/05	12.4	8/11/05	12.54	9/9/05	12.35	10/8/05	12.01
7/14/05	12.55	8/12/05	12.65	9/10/05	12.21	10/9/05	11.76
7/15/05	12.91	8/13/05	12.74	9/11/05	12.07	10/10/05	11.57
7/16/05	13.04	8/14/05	12.82	9/12/05	11.91	10/11/05	11.4
7/17/05	13.1	8/15/05	12.82	9/13/05	11.76	10/12/05	11.17
7/18/05	13.14	8/16/05	12.8	9/14/05	11.58	10/13/05	10.93
7/19/05	13.12	8/17/05	12.8	9/15/05	11.38	10/14/05	10.71
7/20/05	13.08	8/18/05	12.75	9/16/05	11.23	10/15/05	10.53
7/21/05	13.12	8/19/05	12.66	9/17/05	11.08	10/16/05	10.36
7/22/05	13.09	8/20/05	12.6	9/18/05	10.93	10/17/05	10.21
7/23/05	13.04	8/21/05	12.6	9/19/05	10.8	10/18/05	10.09
7/24/05	12.96	8/22/05	12.55	9/20/05	10.7	10/19/05	10.01
7/25/05	12.9	8/23/05	12.53	9/21/05	10.65	10/20/05	9.91
7/26/05	12.86	8/24/05	12.54	9/22/05	10.61	10/21/05	9.86
7/27/05	12.72	8/25/05	12.7	9/23/05	10.52	10/22/05	10
7/28/05	12.6	8/26/05	12.85	9/24/05	10.5	10/23/05	10.2
7/29/05	12.53	8/27/05	12.98	9/25/05	10.53	10/24/05	10.35
7/30/05	12.43	8/28/05	13.15	9/26/05	10.65	10/25/05	10.5
7/31/05	12.35	8/29/05	13.25	9/27/05	10.8	10/26/05	10.5
8/1/05	12.2	8/30/05	13.3	9/28/05	11.05	10/27/05	10.46
8/2/05	12.09	8/31/05	13.3	9/29/05	11.37	10/28/05	10.4
8/3/05	12	9/1/05	13.31	9/30/05	11.48	10/29/05	10.36
8/4/05	11.93	9/2/05	13.25	10/1/05	11.45	10/30/05	10.33
8/5/05	11.85	9/3/05	13.14	10/2/05	11.36	10/31/05	10.28

Date	WL	Date	WL	Date	WL
11/1/05	10.16	11/30/05	7.94	12/29/05	7.1
11/2/05	10.01	12/1/05	7.9	12/30/05	7.09
11/3/05	9.85	12/2/05	7.86	12/31/05	7.07
11/4/05	9.72	12/3/05	7.83		
11/5/05	9.58	12/4/05	7.8		
11/6/05	9.41	12/5/05	7.76		
11/7/05	9.3	12/6/05	7.72		
11/8/05	9.21	12/7/05	7.69		
11/9/05	9.11	12/8/05	7.66		
11/10/05	9.01	12/9/05	7.65		
11/11/05	8.89	12/10/05	7.62		
11/12/05	8.78	12/11/05	7.59		
11/13/05	8.68	12/12/05	7.55		
11/14/05	8.6	12/13/05	7.52		
11/15/05	8.52	12/14/05	7.45		
11/16/05	8.42	12/15/05	7.42		
11/17/05	8.37	12/16/05	7.41		
11/18/05	8.31	12/17/05	7.41		
11/19/05	8.23	12/18/05	7.41		
11/20/05	8.19	12/19/05	7.4		
11/21/05	8.14	12/20/05	7.36		
11/22/05	8.1	12/21/05	7.33		
11/23/05	8.07	12/22/05	7.29		
11/24/05	8.05	12/23/05	7.26		
11/25/05	8.03	12/24/05	7.23		
11/26/05	8.03	12/25/05	7.2		
11/27/05	8.05	12/26/05	7.18		
11/28/05	8.03	12/27/05	7.14		
11/29/05	7.99	12/28/05	7.12		

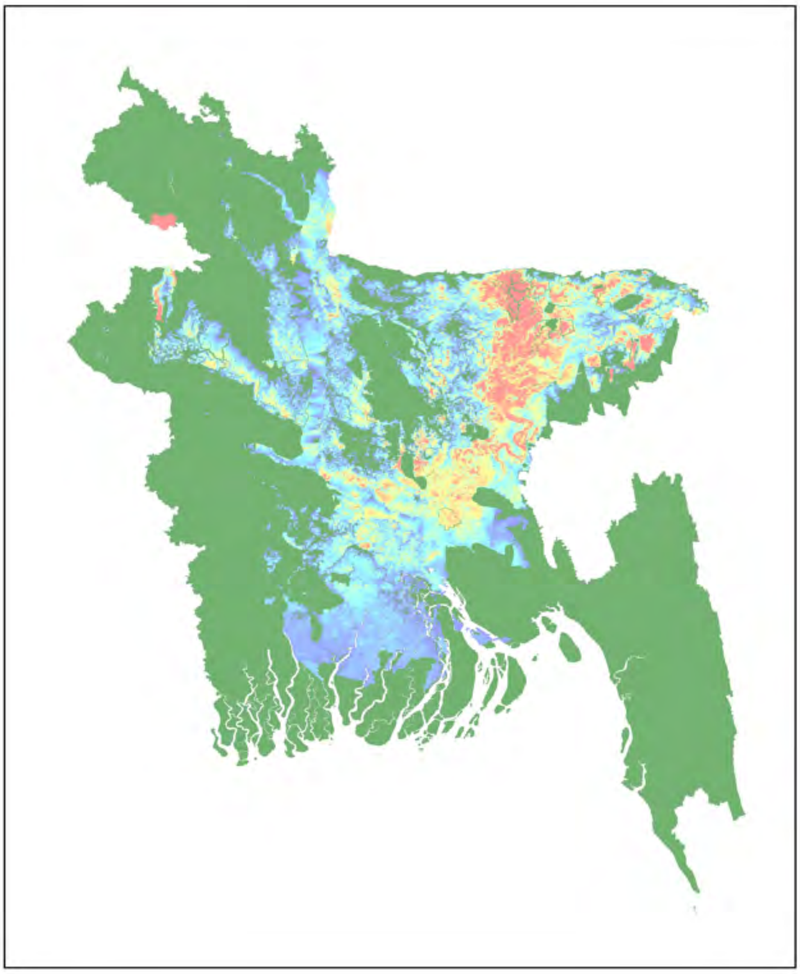
A.3 Yearly peak discharge at Bahadurabad station

Year	Peak Discharge m3/sec	Year	Peak Discharge m3/sec
1956	60400	1985	63700
1957	62500	1986	43100
1958	71300	1987	73000
1959	68500	1988	98300
1960	64800	1989	70700
1961	53800	1990	64300
1962	69400	1991	84100
1963	56400	1992	67000
1964	63100	1993	67000
1965	64200	1994	40900
1966	68900	1995	87000
1967	69600	1996	83800
1968	62300	1997	79219
1969	56000	1998	103129
1970	75000	1999	61970
1972	66600	2000	70602
1973	67300	2001	49243
1974	91100	2002	68351
1975	52200	2003	65287
1976	65600	2004	83946
1977	66600	2005	55341
1978	56600	2006	46792
1979	66100	2007	91742
1980	61200	2008	54962
1981	66500	2009	47949
1982	55900	2010	48534
1983	56200	2011	54445
1984	76800	2012	60603

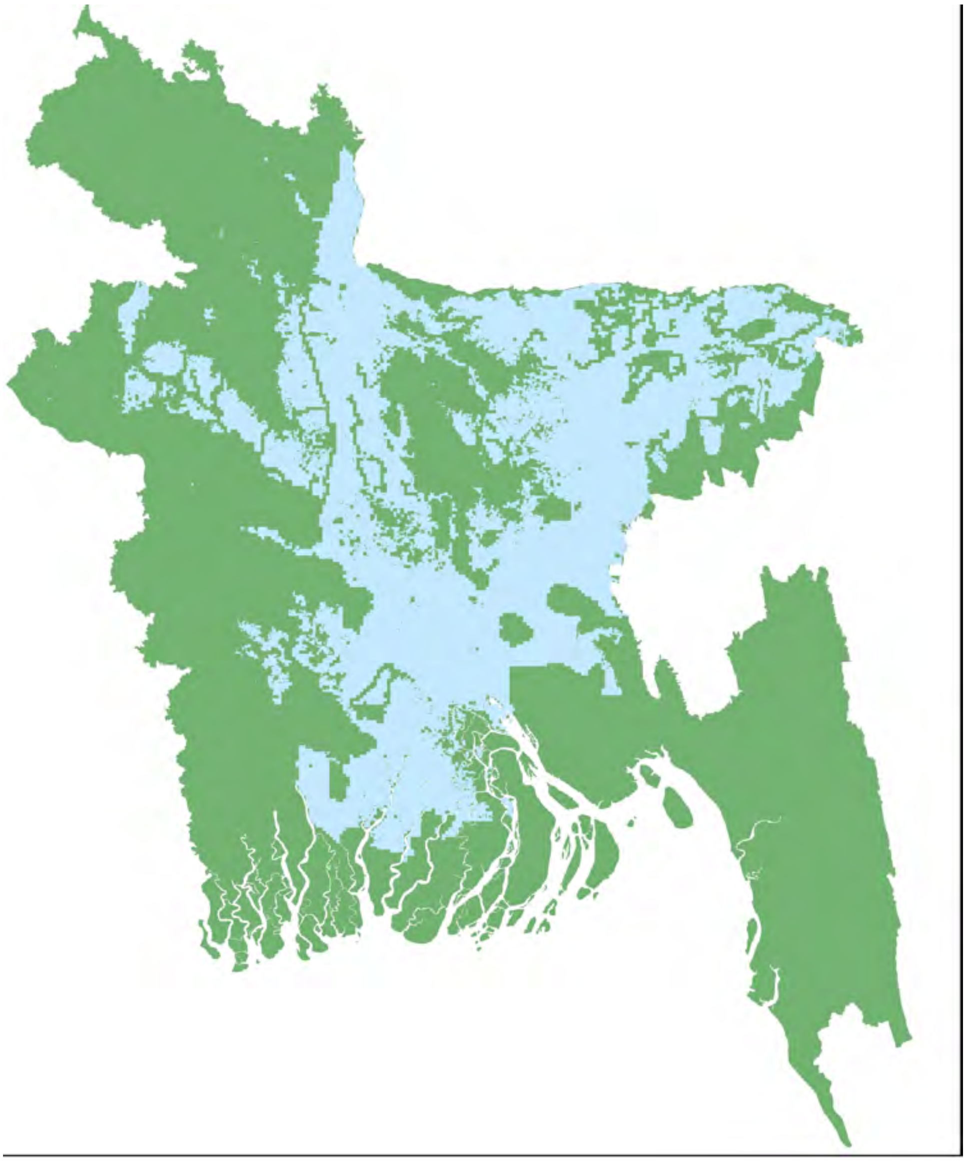
Appendix B

Flood map

B.1 2004 flood map



B.2 2007 flood map



Appendix C

Frequency analysis

Normal Distribution

Return Period (Year)	avg (x) (cumec)	std (s) (cumec)	Z_T	X_T (cumec)
2	66833.58	12633.72005	0.006	66911.83
5	66833.58	12633.72005	0.839	77427.71
10	66833.58	12633.72005	1.281	83020.89
25	66833.58	12633.72005	1.757	89027.16
50	66833.58	12633.72005	2.064	92904.82
100	66833.58	12633.72005	2.337	96362.09

Log Normal Distribution

Return Period (Year)	avg (y) (cumec)	std (s) (cumec)	Z_T	X_T (cumec)
2	11.09	0.187	0.006	65772.05
5	11.09	0.187	0.839	76871.38
10	11.09	0.187	1.281	83519.02
25	11.09	0.187	1.757	91299.08
50	11.09	0.187	2.064	96702.77
100	11.09	0.187	2.337	101789.77

Gumbel Distribution (EV1) Distribution

Return Period (Year)	avg (x) (cumec)	std (s) (cumec)	α	u	y_T	X_T (cumec)
2	66833.58	12633.72	9850.45	61147.90	0.367	64758.22
5	66833.58	12633.72	9850.45	61147.90	1.500	75922.98
10	66833.58	12633.72	9850.45	61147.90	2.250	83315.03
25	66833.58	12633.72	9850.45	61147.90	3.199	92654.90
50	66833.58	12633.72	9850.45	61147.90	3.902	99583.75
100	66833.58	12633.72	9850.45	61147.90	4.600	106461.44

Pearson Type - III Distribution

Return Period (Year)	avg (x) (cumec)	std (s) (cumec)	G_x	Z_T	K_T	X_T (cumec)
2	66833.58	12633.72	0.658	0.006	-0.102	65541.36
5	66833.58	12633.72	0.658	0.839	0.789	76798.07
10	66833.58	12633.72	0.658	1.281	1.329	83618.63
25	66833.58	12633.72	0.658	1.757	1.962	91625.98
50	66833.58	12633.72	0.658	2.064	2.403	97186.20
100	66833.58	12633.72	0.658	2.337	2.816	102410.59

Log Pearson Type - III Distribution

Return Period (Year)	avg (y) (cumec)	std (s) (cumec)	G_y	Z_T	K_T	X_T (cumec)
2	11.10	0.187	-0.051	0.006	-0.102	66482.19
5	11.10	0.187	-0.051	0.839	0.789	77613.08
10	11.10	0.187	-0.051	1.281	1.329	84198.81
25	11.10	0.187	-0.051	1.757	1.962	91831.45
50	11.10	0.187	-0.051	2.064	2.403	97086.32
100	11.10	0.187	-0.051	2.337	2.816	101999.24

C.1 Probability Plot Correlation Coefficient (PPCC)

Normal Distribution

Sample size n = 50 avg x = 66833.58 cumec Std S_x = 12633.72 cumec

Order m	Q Sorting in Descending x_i (cumec)	P_i	T	Z_T	X_T (cumec)
1	103129	0.011	89.500	2.295	95833.54
2	98300	0.031	32.128	1.872	90485.58
3	91100	0.051	19.578	1.639	87537.69
4	87000	0.071	14.079	1.470	85406.79
5	84100	0.091	10.991	1.335	83700.16
6	83946	0.111	9.014	1.221	82255.64
7	83800	0.131	7.640	1.120	80989.63
8	79219	0.151	6.630	1.031	79853.05
9	76800	0.171	5.855	0.948	78814.49
10	75000	0.191	5.243	0.872	77852.50
11	73000	0.211	4.746	0.801	76951.77
12	71300	0.231	4.336	0.734	76100.92
13	70700	0.251	3.990	0.669	75291.23
14	70602	0.271	3.696	0.608	74515.84
15	69600	0.291	3.442	0.549	73769.22
16	69400	0.310	3.221	0.492	73046.85
17	68900	0.330	3.027	0.436	72344.92
18	68500	0.350	2.854	0.382	71660.20
19	68351	0.370	2.700	0.329	70989.89
20	67300	0.390	2.562	0.277	70331.52
21	67000	0.410	2.438	0.226	69682.88
22	67000	0.430	2.325	0.175	69041.96

23	66600	0.450	2.222	0.125	68406.89
24	66600	0.470	2.127	0.075	67775.95
25	66500	0.490	2.041	0.025	67147.43
26	66100	0.510	1.961	-0.025	66519.73
27	65600	0.530	1.887	-0.075	65891.22
28	65287	0.550	1.819	-0.125	65260.27
29	64800	0.570	1.755	-0.175	64625.21
30	64300	0.590	1.696	-0.226	63984.29
31	64200	0.610	1.640	-0.277	63335.65
32	63700	0.630	1.588	-0.329	62677.27
33	63100	0.650	1.539	-0.382	62006.96
34	62500	0.670	1.493	-0.436	61322.24
35	62300	0.690	1.450	-0.492	60620.31
36	61970	0.709	1.409	-0.549	59897.94
37	61200	0.729	1.371	-0.608	59151.33
38	60400	0.749	1.334	-0.669	58375.94
39	56600	0.769	1.300	-0.734	57566.25
40	56400	0.789	1.267	-0.801	56715.40
41	56200	0.809	1.236	-0.872	55814.67
42	56000	0.829	1.206	-0.948	54852.68
43	55900	0.849	1.178	-1.031	53814.11
44	55341	0.869	1.151	-1.120	52677.54
45	53800	0.889	1.125	-1.221	51411.53
46	52200	0.909	1.100	-1.335	49967.01
47	49243	0.929	1.076	-1.470	48260.38
48	46792	0.949	1.054	-1.639	46129.47
49	43100	0.969	1.032	-1.872	43181.58
50	40900	0.989	1.011	-2.295	37833.63
				PPCC	0.9762

Log Normal Distribution

Sample size n = 50 avg y = 11.09 Std S_y = 0.19

Order m	Q Sorting in Descending x_i (cumec)	$Ln(x_i)$	P_i	T	Z_T	X_T (cumec)
1	103129	11.54	0.011	89.500	2.295	100995.06
2	98300	11.50	0.031	32.128	1.872	93295.08
3	91100	11.42	0.051	19.578	1.639	89304.64
4	87000	11.37	0.071	14.079	1.470	86526.83
5	84100	11.34	0.091	10.991	1.335	84364.53
6	83946	11.34	0.111	9.014	1.221	82576.61
7	83800	11.34	0.131	7.640	1.120	81040.82
8	79219	11.28	0.151	6.630	1.031	79686.39
9	76800	11.25	0.171	5.855	0.948	78468.56
10	75000	11.23	0.191	5.243	0.872	77357.14
11	73000	11.20	0.211	4.746	0.801	76330.76
12	71300	11.17	0.231	4.336	0.734	75373.73
13	70700	11.17	0.251	3.990	0.669	74474.15
14	70602	11.16	0.271	3.696	0.608	73622.73
15	69600	11.15	0.291	3.442	0.549	72812.12
16	69400	11.15	0.310	3.221	0.492	72036.32
17	68900	11.14	0.330	3.027	0.436	71290.40
18	68500	11.13	0.350	2.854	0.382	70570.20
19	68351	11.13	0.370	2.700	0.329	69872.21
20	67300	11.12	0.390	2.562	0.277	69193.37
21	67000	11.11	0.410	2.438	0.226	68531.02
22	67000	11.11	0.430	2.325	0.175	67882.77

23	66600	11.11	0.450	2.222	0.125	67246.50
24	66600	11.11	0.470	2.127	0.075	66620.26
25	66500	11.10	0.490	2.041	0.025	66002.24
26	66100	11.10	0.510	1.961	-0.025	65390.73
27	65600	11.09	0.530	1.887	-0.075	64784.11
28	65287	11.09	0.550	1.819	-0.125	64180.80
29	64800	11.08	0.570	1.755	-0.175	63579.23
30	64300	11.07	0.590	1.696	-0.226	62977.82
31	64200	11.07	0.610	1.640	-0.277	62374.97
32	63700	11.06	0.630	1.588	-0.329	61768.97
33	63100	11.05	0.650	1.539	-0.382	61158.03
34	62500	11.04	0.670	1.493	-0.436	60540.19
35	62300	11.04	0.690	1.450	-0.492	59913.31
36	61970	11.03	0.709	1.409	-0.549	59274.95
37	61200	11.02	0.729	1.371	-0.608	58622.31
38	60400	11.01	0.749	1.334	-0.669	57952.11
39	56600	10.94	0.769	1.300	-0.734	57260.45
40	56400	10.94	0.789	1.267	-0.801	56542.53
41	56200	10.94	0.809	1.236	-0.872	55792.32
42	56000	10.93	0.829	1.206	-0.948	55002.08
43	55900	10.93	0.849	1.178	-1.031	54161.50
44	55341	10.92	0.869	1.151	-1.120	53256.30
45	53800	10.89	0.889	1.125	-1.221	52265.82
46	52200	10.86	0.909	1.100	-1.335	51158.16
47	49243	10.80	0.929	1.076	-1.470	49879.72
48	46792	10.75	0.949	1.054	-1.639	48328.22
49	43100	10.67	0.969	1.032	-1.872	46261.11
50	40900	10.62	0.989	1.011	-2.295	42734.11
					PPCC	0.9862

Gumbel Distribution (EV1) Distribution

Sample size n = 50 avg x = 66833.58 cumec Std S_x = 12633.72

α = 9850.44 u = 61147.90

Order m	Q Sorting in Descending x_i (cumec)	P_i	T	Z_T	y_T	X_T (cumec)
1	103129	0.011	89.500	2.295	4.489	105362.88
2	98300	0.031	32.128	1.872	3.454	95171.02
3	91100	0.051	19.578	1.639	2.948	90190.11
4	87000	0.071	14.079	1.470	2.608	86838.33
5	84100	0.091	10.991	1.335	2.350	84294.31
6	83946	0.111	9.014	1.221	2.141	82233.83
7	83800	0.131	7.640	1.120	1.964	80495.26
8	79219	0.151	6.630	1.031	1.811	78986.18
9	76800	0.171	5.855	0.948	1.675	77648.78
10	75000	0.191	5.243	0.872	1.553	76444.46
11	73000	0.211	4.746	0.801	1.441	75346.12
12	71300	0.231	4.336	0.734	1.339	74334.01
13	70700	0.251	3.990	0.669	1.243	73393.27
14	70602	0.271	3.696	0.608	1.154	72512.43
15	69600	0.291	3.442	0.549	1.069	71682.42
16	69400	0.310	3.221	0.492	0.990	70895.96
17	68900	0.330	3.027	0.436	0.914	70147.09
18	68500	0.350	2.854	0.382	0.841	69430.84
19	68351	0.370	2.700	0.329	0.771	68743.04
20	67300	0.390	2.562	0.277	0.704	68080.13
21	67000	0.410	2.438	0.226	0.639	67439.02
22	67000	0.430	2.325	0.175	0.576	66817.02

23	66600	0.450	2.222	0.125	0.514	66211.75
24	66600	0.470	2.127	0.075	0.454	65621.08
25	66500	0.490	2.041	0.025	0.395	65043.05
26	66100	0.510	1.961	-0.025	0.338	64475.90
27	65600	0.530	1.887	-0.075	0.281	63917.95
28	65287	0.550	1.819	-0.125	0.225	63367.64
29	64800	0.570	1.755	-0.175	0.170	62823.47
30	64300	0.590	1.696	-0.226	0.115	62283.95
31	64200	0.610	1.640	-0.277	0.061	61747.63
32	63700	0.630	1.588	-0.329	0.007	61213.02
33	63100	0.650	1.539	-0.382	-0.048	60678.60
34	62500	0.670	1.493	-0.436	-0.102	60142.74
35	62300	0.690	1.450	-0.492	-0.157	59603.73
36	61970	0.709	1.409	-0.549	-0.212	59059.66
37	61200	0.729	1.371	-0.608	-0.268	58508.37
38	60400	0.749	1.334	-0.669	-0.325	57947.42
39	56600	0.769	1.300	-0.734	-0.383	57373.90
40	56400	0.789	1.267	-0.801	-0.443	56784.32
41	56200	0.809	1.236	-0.872	-0.505	56174.34
42	56000	0.829	1.206	-0.948	-0.569	55538.43
43	55900	0.849	1.178	-1.031	-0.637	54869.27
44	55341	0.869	1.151	-1.120	-0.710	54156.81
45	53800	0.889	1.125	-1.221	-0.788	53386.52
46	52200	0.909	1.100	-1.335	-0.874	52536.06
47	49243	0.929	1.076	-1.470	-0.973	51567.93
48	46792	0.949	1.054	-1.639	-1.090	50410.46
49	43100	0.969	1.032	-1.872	-1.244	48893.18
50	40900	0.989	1.011	-2.295	-1.503	46344.69
					PPCC	0.9855

Pearson Type- III Distribution

Sample size n = 50 avg x = 66833.58 cumec Std S_x = 12633.72

skewness G_x = 0.66

Order m	Q Sorting in Descending x_i (cumec)	P_i	T	Z_T	X_T	X_T (cumec)
1	103129	0.011	89.500	2.295	2.752	101595.31
2	98300	0.031	32.128	1.872	2.125	93680.60
3	91100	0.051	19.578	1.639	1.800	89572.60
4	87000	0.071	14.079	1.470	1.574	86713.00
5	84100	0.091	10.991	1.335	1.397	84488.16
6	83946	0.111	9.014	1.221	1.252	82649.85
7	83800	0.131	7.640	1.120	1.127	81072.15
8	79219	0.151	6.630	1.031	1.017	79682.08
9	76800	0.171	5.855	0.948	0.918	78433.47
10	75000	0.191	5.243	0.872	0.828	77295.17
11	73000	0.211	4.746	0.801	0.745	76245.13
12	71300	0.231	4.336	0.734	0.668	75267.16
13	70700	0.251	3.990	0.669	0.595	74348.97
14	70602	0.271	3.696	0.608	0.526	73481.00
15	69600	0.291	3.442	0.549	0.461	72655.64
16	69400	0.310	3.221	0.492	0.398	71866.73
17	68900	0.330	3.027	0.436	0.338	71109.19
18	68500	0.350	2.854	0.382	0.281	70378.76
19	68351	0.370	2.700	0.329	0.225	69671.82
20	67300	0.390	2.562	0.277	0.170	68985.25
21	67000	0.410	2.438	0.226	0.117	68316.31
22	67000	0.430	2.325	0.175	0.066	67662.60

23	66600	0.450	2.222	0.125	0.015	67021.95
24	66600	0.470	2.127	0.075	-0.035	66392.40
25	66500	0.490	2.041	0.025	-0.084	65772.12
26	66100	0.510	1.961	-0.025	-0.133	65159.41
27	65600	0.530	1.887	-0.075	-0.181	64552.68
28	65287	0.550	1.819	-0.125	-0.228	63950.34
29	64800	0.570	1.755	-0.175	-0.276	63350.88
30	64300	0.590	1.696	-0.226	-0.323	62752.76
31	64200	0.610	1.640	-0.277	-0.370	62154.43
32	63700	0.630	1.588	-0.329	-0.418	61554.27
33	63100	0.650	1.539	-0.382	-0.466	60950.59
34	62500	0.670	1.493	-0.436	-0.514	60341.55
35	62300	0.690	1.450	-0.492	-0.563	59725.15
36	61970	0.709	1.409	-0.549	-0.612	59099.13
37	61200	0.729	1.371	-0.608	-0.663	58460.94
38	60400	0.749	1.334	-0.669	-0.714	57807.58
39	56600	0.769	1.300	-0.734	-0.768	57135.51
40	56400	0.789	1.267	-0.801	-0.823	56440.40
41	56200	0.809	1.236	-0.872	-0.880	55716.86
42	56000	0.829	1.206	-0.948	-0.940	54958.00
43	55900	0.849	1.178	-1.031	-1.004	54154.66
44	55341	0.869	1.151	-1.120	-1.072	53294.27
45	53800	0.889	1.125	-1.221	-1.146	52358.74
46	52200	0.909	1.100	-1.335	-1.228	51320.30
47	49243	0.929	1.076	-1.470	-1.322	50132.67
48	46792	0.949	1.054	-1.639	-1.435	48708.39
49	43100	0.969	1.032	-1.872	-1.582	46842.76
50	40900	0.989	1.011	-2.295	-1.827	43756.92
					PPCC	0.9861

Log Pearson Type- III Distribution

Sample size n = 50 avg y = 11.10 cumec Std S_y = 0.1873

skewness G_y = -0.05

Order m	Q Sorting in Descending x_i (cumec)	P_i	T	Z_T	y	K_T	X_T (cumec)
1	103129	0.011	89.500	2.295	11.544	2.259	101233.87
2	98300	0.031	32.128	1.872	11.496	1.851	93776.86
3	91100	0.051	19.578	1.639	11.420	1.624	89882.40
4	87000	0.071	14.079	1.470	11.374	1.460	87159.11
5	84100	0.091	10.991	1.335	11.340	1.328	85032.19
6	83946	0.111	9.014	1.221	11.338	1.216	83268.80
7	83800	0.131	7.640	1.120	11.336	1.118	81750.67
8	79219	0.151	6.630	1.031	11.280	1.030	80409.18
9	76800	0.171	5.855	0.948	11.249	0.949	79200.85
10	75000	0.191	5.243	0.872	11.225	0.874	78096.34
11	73000	0.211	4.746	0.801	11.198	0.804	77074.86
12	71300	0.231	4.336	0.734	11.175	0.737	76121.10
13	70700	0.251	3.990	0.669	11.166	0.674	75223.43
14	70602	0.271	3.696	0.608	11.165	0.613	74372.81
15	69600	0.291	3.442	0.549	11.151	0.555	73562.02
16	69400	0.310	3.221	0.492	11.148	0.498	72785.21
17	68900	0.330	3.027	0.436	11.140	0.443	72037.53
18	68500	0.350	2.854	0.382	11.135	0.389	71314.91
19	68351	0.370	2.700	0.329	11.132	0.337	70613.88
20	67300	0.390	2.562	0.277	11.117	0.285	69931.43
21	67000	0.410	2.438	0.226	11.112	0.234	69264.94
22	67000	0.430	2.325	0.175	11.112	0.183	68612.06

23	66600	0.450	2.222	0.125	11.106	0.133	67970.67
24	66600	0.470	2.127	0.075	11.106	0.083	67338.84
25	66500	0.490	2.041	0.025	11.105	0.033	66714.76
26	66100	0.510	1.961	-0.025	11.099	-0.016	66096.74
27	65600	0.530	1.887	-0.075	11.091	-0.066	65483.15
28	65287	0.550	1.819	-0.125	11.087	-0.116	64872.39
29	64800	0.570	1.755	-0.175	11.079	-0.167	64262.89
30	64300	0.590	1.696	-0.226	11.071	-0.217	63653.05
31	64200	0.610	1.640	-0.277	11.070	-0.269	63041.23
32	63700	0.630	1.588	-0.329	11.062	-0.321	62425.71
33	63100	0.650	1.539	-0.382	11.052	-0.375	61804.65
34	62500	0.670	1.493	-0.436	11.043	-0.429	61176.06
35	62300	0.690	1.450	-0.492	11.040	-0.485	60537.71
36	61970	0.709	1.409	-0.549	11.034	-0.543	59887.11
37	61200	0.729	1.371	-0.608	11.022	-0.603	59221.38
38	60400	0.749	1.334	-0.669	11.009	-0.665	58537.12
39	56600	0.769	1.300	-0.734	10.944	-0.730	57830.30
40	56400	0.789	1.267	-0.801	10.940	-0.798	57095.93
41	56200	0.809	1.236	-0.872	10.937	-0.870	56327.77
42	56000	0.829	1.206	-0.948	10.933	-0.947	55517.79
43	55900	0.849	1.178	-1.031	10.931	-1.031	54655.26
44	55341	0.869	1.151	-1.120	10.921	-1.123	53725.35
45	53800	0.889	1.125	-1.221	10.893	-1.225	52706.54
46	52200	0.909	1.100	-1.335	10.863	-1.342	51565.63
47	49243	0.929	1.076	-1.470	10.805	-1.480	50246.76
48	46792	0.949	1.054	-1.639	10.753	-1.653	48643.25
49	43100	0.969	1.032	-1.872	10.671	-1.893	46501.96
50	40900	0.989	1.011	-2.295	10.619	-2.332	42835.81
						PPCC	0.9857