The effect of climate and anthropogenic change on the spatial variability of turbidity maxima in the southwest delta of Bangladesh.

by

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STATEMENT

I hear by declare that this work has been carried out by me and the thesis has been composed by me and has not been submitted for any other degree or professional qualification.

This work is presented to obtain a masters' degree in Water and Coastal Management (WACOMA).

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D. Alfredo Izquierdo González, Profesor del Departamento de **Fizică Aplicată** de la Universidad de Cádiz y D. Hans Middelkoop**,** Profesor del Departamento de **Departamento de Geografía Física** de la Universidad de **Utrecht,** como sus directores

HACEN CONSTAR:

Que esta Memoria, titulada **"(El efecto del cambio climático y antropogénico sobre la variabilidad espacial de los máximos de turbidez en el delta sudoeste de Bangladesh)"**, presentada por D. Morsheda Begum, resume su trabajo de Tesis de Master y, considerando que reúne todos los requisitos legales, autorizan su presentación y defensa para optar al grado de Master Erasmus Mundus in Water and Coastal Management (WACOMA).

Cádiz, (10/11/2018)

Dr. Alfredo Izquierdo González	**Dr. Hans Middelkoop**

I dedicate this master thesis to ……………………

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ABSTRACT

Outline of the thesis

The southwest area of Bangladesh is a tide dominated delta and has a complex dynamics between sediment, season-dependent river discharge and tide. In this study, we apply 1D hydrodynamic model (MIKE 11) to investigate the fluvial dynamics with allowance for tidal influence in this region. An advection-dispersion model for cohesive sediment was applied and used to study the changes in suspended sediment concentration and sediment load. The results show the influence of seasonality and and interannual variability in the tidal range spatial pattern in the area of study. Tidal range shows maximum values in the western part (Sibsa and Arpangasia-Kobadak river) irrespective of seasons. During Monsoon, the area of tidal influence reduces shifting its boundary closer to sea. In our study area the sediment load is higher in the eastern part than the western part, as it is under the influence of the main sediment carrying channel, the Meghna river (lower). Regarding the sediment load along Gorai-Madhumati-Kocha-Baleswar river system, it is constant in Gorai river and then it reduces closer to the sea. The Arial khan and Meghna spills delivers sediment from the Meghna (lower) to the eastern part. We have also performed simulations to assess the impact of the climate change on the river hydrodynamics and the tidal influence in the delta system for years 2050 and 2080. Model results show that the expected changes fall within the natural interannual variability assessed from dry, flood and normal years.

RESUMEN

El area suroeste de Bangladesh es un estuario mareal que presenta unas interacciones muy complejas entre la dinámica sedimentaria, la fuertemente estacional descarga fluvial y la marea. En este estudio se aplica un modelo hidrodinámico unidimensional (MIKE 11) para investigar la dinámica fluvial teniendo en cuenta la influencia de la dinámica mareal en esta región. Además se aplica un modelo de advección-dispersión para sedimentos cohesivos para estudiar los cambios en la concentración de los sedimentos en suspensión y en la carga sedimentaria. Los resultados muestran la influencia de la estacionalidad y la variabilidad interanual en la distribución espacial del rango de marea en la región de estudio. El rango de marea presenta valores máximos en la zona occidental del delta (ríos Sibsa y Arpangasia-Kobadak) independientemente de la estación del año. Durante el monzón el área del delta sometido a la influencia de la marea se reduce, desplazando su límite hacia la costa. La carga sedimentaria es mayor en la zona oriental del delta que en la occidental, puesto que recibe los aportes del principal transportador de sedimentos, el río Meghna. La carga sedimentaria a lo largo del sistema fluvial Gorai-Madhumati-Kocha-Baleswar permanece constante a lo largo del río Gorai,

y luego gradualmente se reduce hasta llegar al mar. Los ríos he Arial Khan y Meghna vierten sedimentos procedentes del Meghna a la parte oriental del delta. También se han realizado simulaciones para evaluar el impacto del cambio climático en la dinámica fluvial y la influencia de marea en el sistema deltaico en los años 2050 y 2080. Los resultados del modelo sugieren que los cambios esperados están dentro de la variabilidad interanual estimada a partir de años lluviosos, secos y el año promedio.

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CHAPTER 1: Introduction

1.1 Background

Bangladesh is the low lying delta of three major rivers called Ganges, Brahmaputra and Meghna with a population of about 142 million (Bangladesh Bureau of Statistics, 2012). The coastal zone of Bangladesh is low-lying with 62% of the land having an elevation less than 3 m above mean seal level (AMSL) and 86% less than 5 meters AMSL (Mohal *et al.* 2007). About 49% of total population of Bangladesh lives in the low elevation coastal zones which is predicted to increase in the future with high population growth (Neumann et al., 2015). Bangladesh could lose one fourth of the landmass due to sea level rise at the end of year 2100 (Ericson *et al*., 2005). With the sea level rise, about 3 million people will be directly affected by year 2050 (Ericson *et al*., 2005). The land subsidence in the delta will relatively increase the effect of sea level rise. The over extraction of the ground water will speed up the subsidence. It will also increase the salt water intrusion inland causing impacts change in the ecosystem of the coastal region, consequently destroying it.

Bangladesh has 123 polders in the coastal areas most of which is in the south western part of the country (Mohal *et al*., 2007). Polders are the areas surrounded by dikes to protect the area from high water level in the rivers and sea. They were constructed in the 1960s to improve the food production and livelihood of the coastal areas. Due to the embankment, these areas have been deprived of natural sedimentation flow and can't sustain the land level, resulting in subsidence. The overall mean reported sedimentation rate was 5.6 mm/yr (Brown & Nicholls, 2015). Temporal and spatially, rates varied between -1.1 mm/yr (i.e. uplift) and 43.8 mm/yr (Brown and Nicholls, 2015).

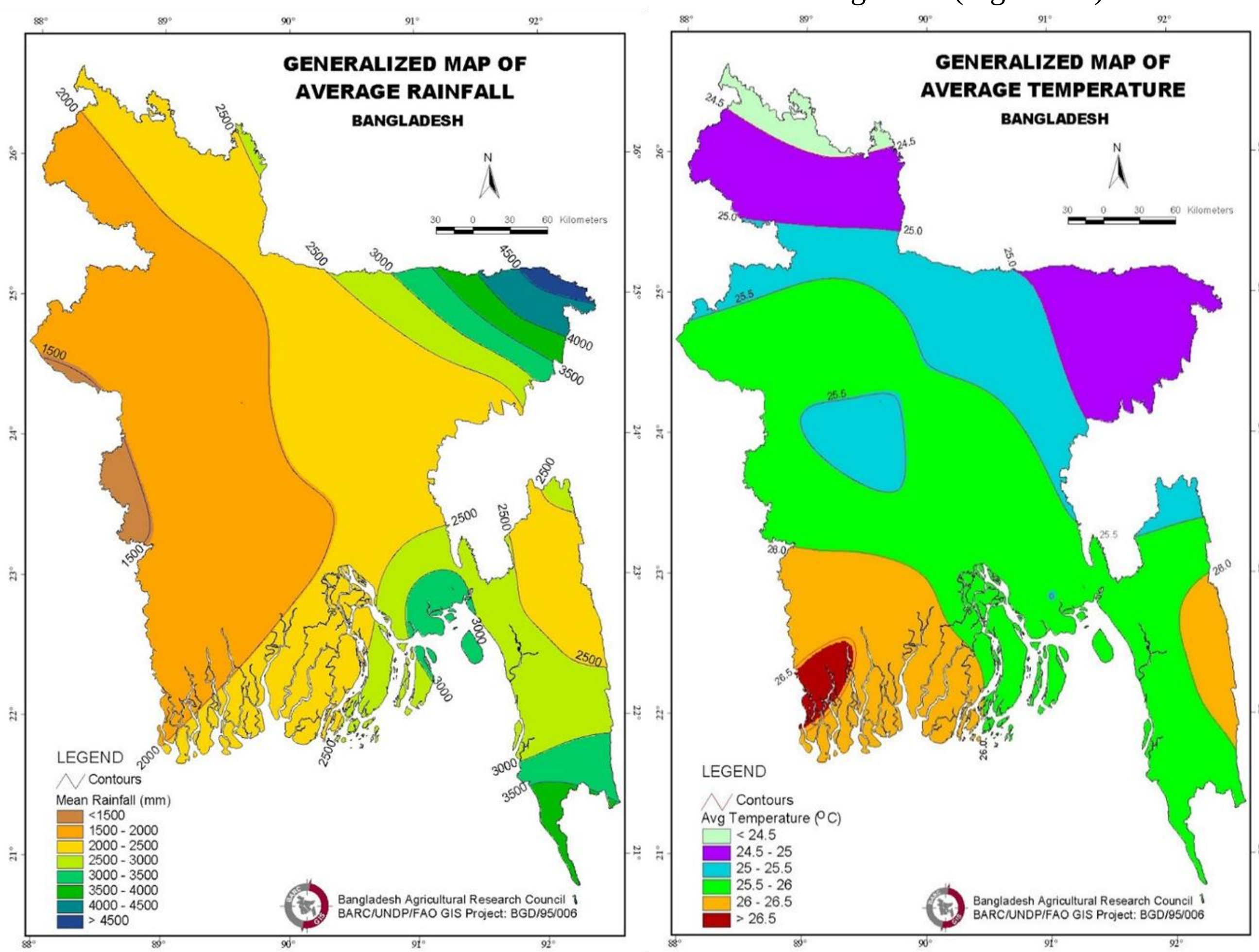
The rivers of Bangladesh carry a huge amount of sediment from the upstream catchments. Maximum sediment concentration of 9.74 g/l at 0.5 meter above channel bed during spring tide was recorded at the north of Urir Char in south eastern part of Bangladesh (Ahmed & Louters, 1997). Previously, no studies have been conducted to use this sediment -water to make the land elevation higher using controlled flooding inside the polders. Sediment trapping in the turbidity maxima (TM) is extremely variable in different estuaries or at different times in the same estuary (Wu et al., 2012). How related processes impact the turbidity maxima behavior and its structure has not yet been completely clear in the south-western region of Bangladesh.

The south western region of Bangladesh constitutes 32% of total land area in Bangladesh and hosts about 28% of the population (i.e. nearly 42 million). This region is ravaged by periodic water logging, salinity intrusion, cyclonic storm surges and land subsidence. There are numerous tidal creeks with an intricate system of biodiversity which includes Sundarbans, the largest mangrove forest in the world (Solidarites International & Uttaran, 2009). The case study area is selected considering the regional scale to understand the movement of turbidity maxima in the south western delta of Bangladesh.

1.2 Climate

Bangladesh is located in a tropical monsoon region characterized by wide seasonal variations in rainfall, temperatures and humidity. There are three distinct seasons in Bangladesh: a hot, humid summer from March to May; a cool, rainy monsoon season from June to October; and a cool, dry winter from November to February. April is the warmest month in most parts of the country. January is the coldest month (Ahmed, n.d.). The period comprising October and November is termed as post-monsoon and the period from March-May is termed as pre-monsoon. In this study, three seasons are considered: pre-monsoon, monsoon and post-monsoon

In general, the average rainfall changes from 4500 mm to 1500 mm and the average temperature increases from 24.5°C to 26.5°C from northeast to southwest of Bangladesh (Figure 1-1)



(a) (b)

Figure 1-1:(a) Generalized map of average rainfall in Bangladesh (b) Generalized map of average temperatures in Bangladesh (BARC, 2014)

1.3 Study Area

The Ganges-Brahmaputra-Meghna (GBM) delta is a dynamic delta with about a billion sediment load per year with a complex river network. According to an assessment done by (Van Driel et al., 2015), the GBM delta is the most vulnerable delta in the World considering four delta vulnerability indicators (a) relative sea level rise (RSLR); (b) wetland ecological threat; (c) population pressure; and (d) delta governance.

The southwest area of Bangladesh is an important part of the GBM delta and Ganges Dependent Area (GDA). For water resources planning, Bangladesh has been divided in regions based on hydrological conditions. (Chowdhury, 2014). The southwest area mainly comprises of two such regions: southwest region and south central region. The southwest area is the study area for the research project. It is located between 88°33'30"E to 90°39'25"E longitude and 21°42'16"N to 24°9'54"N latitude.

The southwest area is characterized by complex sediment dynamics, tidal dynamics and salinity. At the eastern limit of the southwest area, the Meghna estuary carries 1037 tons of suspended sediment of which 525 million tons delivered to the sea (Islam, Begum, Yamaguchi, & Ogawa, 1999). A huge part of the exported sediment re-enters into the southwest area through numerous tidal rivers, creeks (Haque, Sumaiya, & Rahman, 2016). On the other hand, sedimentation causing serious drainage and navigation issues in all of the river systems of the southwest area (Shampa & Pramanik, 2012). But sediment dynamics has not yet been studied in a regional scale using the numerical model which makes the south-west area of Bangladesh, an ideal place to study movement of turbidity maxima

The eastern part of the study area receives a considerable amount of freshwater from Padma river and Meghna (lower) river through Arialkhan, Bishkhali and Buriswar River (refer to Figure 1-2) As a result the salinity is low (0-1 ppt) Khan, Z. H., et al (2014). Whereas in the western part, the only source of freshwater is Gorai river. The Gorai river flow considerably decreases during the dry season causing the salinity in the western part, quite high. (Chowdhury, 2014)

The study area is severely affected by natural hazards like arsenic contamination, cyclonic storms etc.

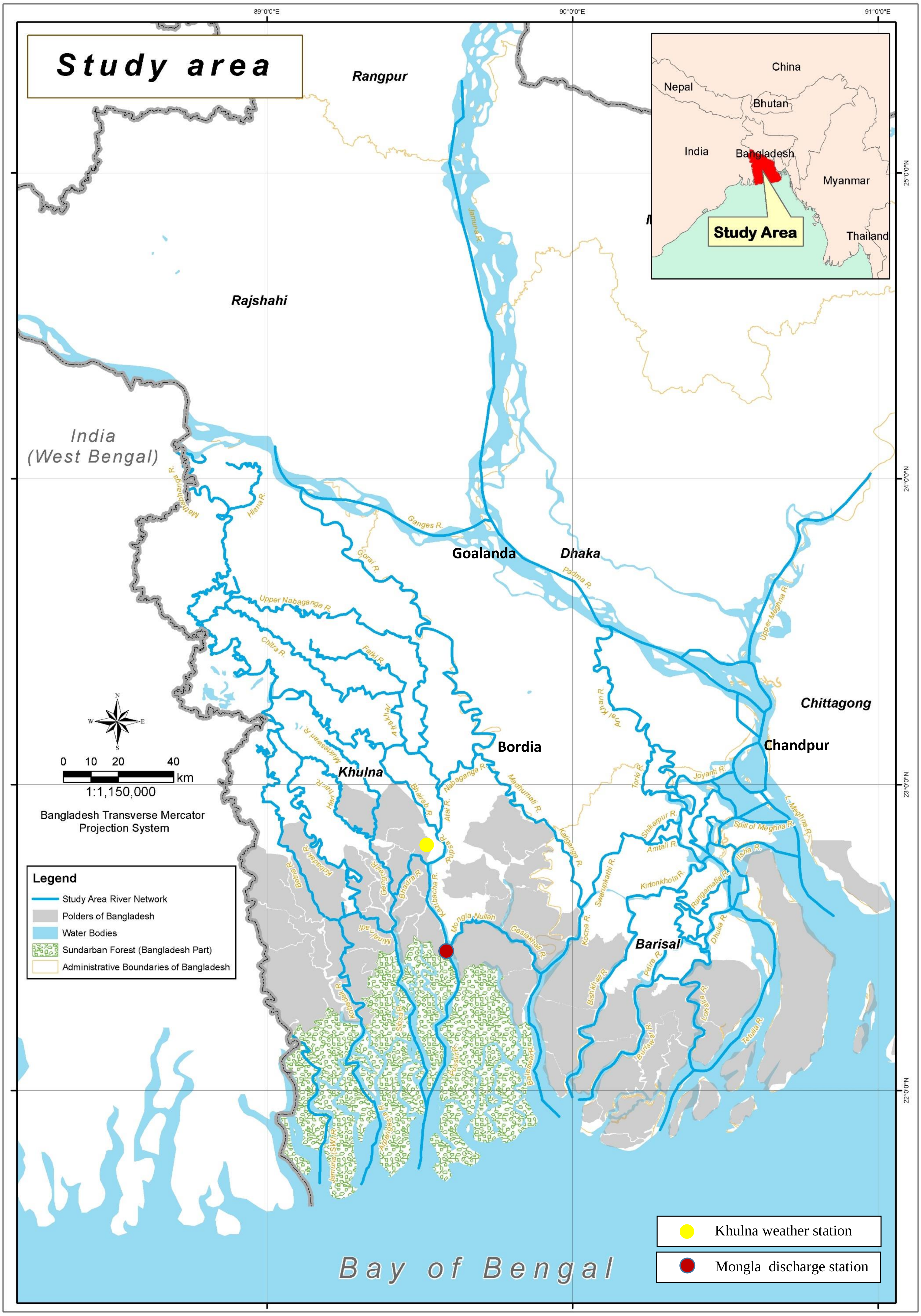


Figure 1-2: The alignment of river network in the study area

1.4 Ecosystem of the Study Area

The southwest coastal region of Bangladesh provides one of the world's richest ecosystems characterized by fertile soils and mangrove forests (Md. Shahadat Hossain & Hossain, 2001) The area experiences a subtropical monsoonal climate with an annual rainfall of 1,600–1,800 mm (see Figure 1-1).

The world's largest mangrove forest, The Sundarbans, covering about one million ha, is situated in this region (Gopal & Chauhan, 2006). The Sundarbans biodiversity includes about 350 species of vascular plants, 250 fishes and 300 birds, besides numerous species of phytoplankton, fungi, bacteria, zooplankton, benthic invertebrates, mollusks, reptiles, amphibians and mammals. Species composition and community structure vary east to west, and along the hydrological and salinity gradients. Sundarbans is the habitat of many rare and endangered animals (Batagur baska, Pelochelys bibroni, Chelonia mydas), and especially the Royal Bengal tiger (Panthera tigris). Enormous amounts of sediments carried by the rivers contribute to the Sundarbans expansion and counterbalance subsidence in this area..

The rivers in the eastern part of the southwest region is the breeding ground for riverine and estuarine fish like Hilsa: *Tenualosa ilisa*, sea bass, vetki, Coral: *Latescal carifer* and prawn brood *Macrobrachium rosenbergii* nursing ground (International Union for Conservation of Nature and Natural Resources, 2015).

The regulation of river flows by a series of dams, barrages and embankments for diverting water upstream for various human needs and for flood control has caused large reduction in freshwater inflow and seriously affected the biodiversity in the Sundarban and the surrounding area.

1.5 State of The Art

A study was carried by (Islam et al. 1999) focused on basin denudation and sedimentation of the Ganges and Brahmaputra rivers. The study investigated that the high load of sediment that reflects the very high rate of denudation in their drainage basins. The average mechanical denudation rate for the Ganges and Brahmaputra basins together was estimated in 365 mm 10^{-3} year. The total suspended sediment load transported by these rivers is 1037 million tons. About 525 million tons of this transported sediment load are delivered to the coastal area of Bangladesh and the remaining 512 million tons are deposited within the lower basin. Of the deposited load, about 289 million tons are deposited on the floodplains of these rivers. The remaining 223 million tons are deposited within the river channels, resulting in aggradation of the channel bed at an average rate of about 3.9 cm yr^{-1}. The channel bed aggradation rate is much higher for the Ganges.

A study was carried by (Barua, 1990) revealed that the movement of suspended sediment in the Meghna estuary appears to be associated with the ebb dominance or flood dominance of some channels and the net import of suspended sediment takes place through flood channels while the net export occurs through ebb channels. The aspect ratio (mean depth of flow divided by width of the channel) is lower for the channels having net flood flow and vice versa. The measurements show that the suspended sediment concentration (SSC), both in the flood channel and in the ebb channel, is dependent on the tidal range: the average spring tidal SSC is about twice that of the neap tide, and locations with higher tidal range show higher magnitudes of SSC. The upper limit of the zone of turbidity maximum coincides with the zone of salinity intrusion (IECO, 1961; LDL, 1968; Eysink, 1983) and the lower limit lies at approximately 10 m depth contour where there is density driven circulation of suspended sediment. There is a time lag of SSC peak with respect to the peak discharge for both flood and ebb flow, which creates a hysteresis relationship during the semi-diurnal cycle and during the spring-neap cycle. There is a gradient in the magnitude of SSC for all hours of semi-diurnal tidal cycle.

Haque et al. (2016) studied the flow distribution and sediment transport mechanism in the estuarine systems of Ganges-Brahmaputra-Meghna delta. In this study 1D and 2D (HEC-RAS & Delft3D, respectively) dynamic models were prepared to study the flow distribution patterns and then the flow distribution parameters were used as proxy variables to study sediment transport mechanism in the region. The estuarine systems were divided in three areas namely eastern estuarine system (EES), central estuarine system (CES) and western estuarine system (WES) based on the amount of receiving freshwater flow. The study showed that the estuarine system has a clockwise circulation, because of which the sediment enters the CES from the sea and make sedimentation. The study used only publicly available data.

Jahan el al. (2015) focused on the spatial variation of sediment concentration and some other variables such as water pH, alkalinity, salinity , phosphate concentration, carbonate and total organic matter contents in GBM delta estuaries. The study found that the sediment concentration is 20 times higher in marine dominated estuaries than the river dominated estuaries which indicates a net landward sediment transport which in turn causes accretion in mud flats. The study used only publicly available data.

Overeem et al. (2014) associated the daily incoming sediment flux in the Ganges-Brahmaputra delta system with a distributed hydrological basin model, WBM-SED, and found that sedimentation rates in tidal delta are ~1.1 cm/yr. The modeled sedimentation has a strong longitudinal grain size trend. The model predicts strong downstream fining of sediments.

A study was carried out by Nihal et al. (2016) evaluated the fluvial and tidal inundation patterns resulting from temperature increase and sea level rise. The GBM delta is perceived to be at great risk of increased flooding due to climatic impacts and submergence from sea-level rise. To study the impacts, two time horizons, namely mid and end of twenty first century were considered.

1.6 Problem Statement

The south west area of Bangladesh is a part of the Ganges-Brahmaputra-Delta which is affected by tidal flooding, low dry season flow, subsidence in the polders, cyclones and storm surges, dike breaching, salinity intrusion, sea level rise and climate change etc. The problem complexity increases when sedimentation in the river bed and subsidence in the polder is observed. Yet, there is no study on sediment dynamics focusing on the south-western rivers of Bangladesh.

Currently, there has not been any investigation on turbidity maxima in the south-western region of Bangladesh using 1D sediment transport model. A study conducted previously by Elahi et al. (2015) for the coastal areas of Bangladesh includes static investigations of the sedimentation patterns in the south-western region of Bangladesh.

1.7 Research Objective

The following objectives will be achieved in the study:

i. Develop 1D sediment transport model for the south western region of Bangladesh.
ii. Scenario development including sea level rise.
iii. Simulation and analysis of the scenarios using the developed model.
iv. Investigate the movement of turbidity maxima in the major rivers.

CHAPTER 2: Methodology

The details of the developed methodology is discussed in this section. The section focuses on the process of developing the mathematical model of cohesive sediment transport using available data and scenario development and result comparison.

2.1 Flow Chart

To achieve the research objectives, an appropriate methodology was needed to be developed. The methodology was developed considering the information available from previous studies and objectives of the research. A flow chart is presented in Figure 2-1 to describe the steps followed to carry out the research. Different steps presented in the flow chart are discussed later in the chapter.

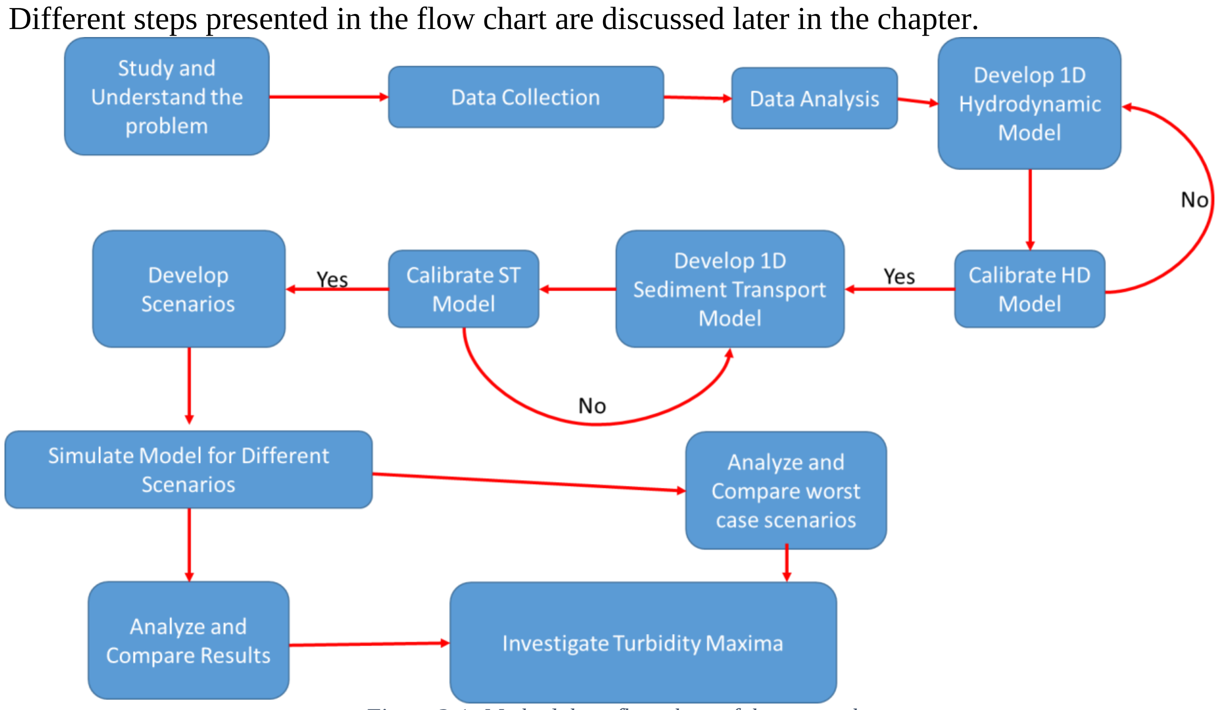


Figure 2-1: Methodology flow chart of the research

2.2 Understanding the Nature of the Problem

Recognizing and understanding a problem is the first step of solving it. In Bangladesh, studies on sediment dynamics for the south-western rivers has not been done in regional scale, which is very important for river basin sediment management. There are detailed studies on river hydrodynamics, river water salinity in a regional scale; but sediment dynamics was often set aside because of its complexity and the large uncertainty of the results.

The review of literature provided the necessary knowledge about the problem. The information from the previous researches was used. Steps were taken in this thesis to reduce the identified knowledge gap.

2.3 Data Collection

There was no data collection from field for this research project. The calibration and validation data for hydrodynamic model such as discharge (Q) and water level was provided from the project of “Living polders: dynamic polder management for sustainable livelihoods, applied to Bangladesh”. The required data for advection-dispersion model for cohesive sediment was collected from published studies in technical reports and journals. In this thesis project, data collection was a big challenge.

2.4 Data Analysis

The collected data was checked for errors. The bed level of the river cross-sections were checked for any aberration. The collected water level and discharge data were analyzed to establish the dominant time-scales of variability.

2.5 Development of Cohesive Sediment Transport Model

Cohesive sediment is defined as sediment with a grain size less than 63µm. Estuarine processes such as flocculation, settling/scour lag and others makes difficult to predict the behavior of cohesive sediment without extensive knowledge of the study area and field data. The use of numerical modelling tools has however increased the understanding of fine-grained sediment dynamics. The chapter (refer to CHAPTER 4:) describes the required considerations in setting up an advection-dispersion numerical model for cohesive sediment.

The development of the hydrodynamic model is the first step of developing an advection-dispersion model for cohesive sediment transport. The hydrodynamic model used in this research project is derived from the south-west regional hydrodynamic model of Institute of Water Modelling (IWM)

2.6 Development of Scenarios

There are three scenarios. The scenarios for model simulation were developed considering the total rainfall in a year in Khulna weather station of the study area (see Figure 1-2); based on which base, wet and dry years were determined.

(Table 2-1: Selection of years for different scenarios

Year	Total Rainfall (mm)	Scenario
2000	1756	Base Year
2001	1629	Dry year
2004	2213.7	Flood year

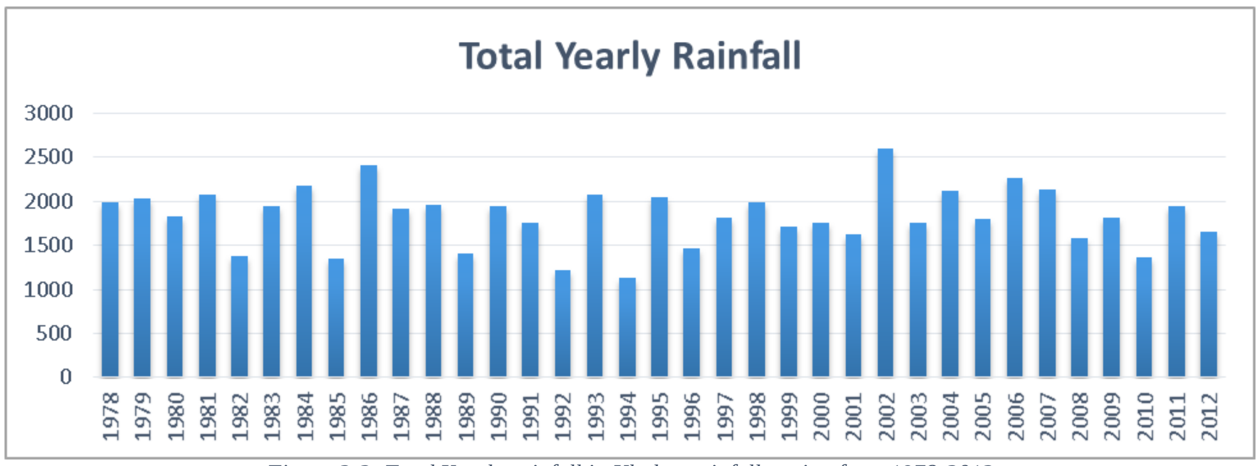


Figure 2-2: Total Yearly rainfall in Khulna rainfall station from 1978-2012

It must be noted that the years 2000, 2001 and 2004 was selected based on the requirements of the project "Living polders: dynamic polder management for sustainable livelihoods, applied to Bangladesh" in Utrecht University and data availability. The rainfall data was provided by the same project.

There was also other two scenarios based on climate change and sea level rise.

Table 2-2: The change of discharges for the year 2050 and 2080 from the base year

River name	Type of flow	Year 2000 (m^3/s)	Year 2050	Year 2080
Ganges	Peak Flow	60137	66578	69801
Brahmaputra		71900	81786	86280
Meghna		17237	20425	20857

To develop the scenario for climate change, the value of mean sea level is increased by 0.18 m and 0.32 m for year 2050 and 2080 respectively at the river mouth in all of the downstream boundaries of the hydrodynamic model (refer to Figure 4-1).

2.7 Analyze and Compare the Result for Different Scenarios

The model results for base, flood and dry years were compared to understand the distribution of tidal discharge, propagation of tidal range in different scenarios. They were also compared with climate change scenario from AR4 (SRES A1b) for the year 2050 and 2080 (Solomon & Qin, 2013). The sediment dynamics were analyzed.

2.8 Investigate the Movement of Turbidity Maxima for Major South-western Rivers

(Hughes et al. 1998; Dyer, 1986; Eisma, 1993) reported that the turbidity maximum zone exists toward the head of the estuary where the turbidity of the water is markedly higher than that observed further landward or seaward.

The formation of a turbidity maxima is governed by two mechanisms: a) tidal asymmetry b) density circulation (Toublanc et al. 2016). The effect of these two mechanisms was analyzed.

The movement of the turbidity maxima was investigated with the help of a one dimensional advection-dispersion model for cohesive sediment. Only suspended sediment concentration was considered for the investigation as other components of turbidity data, such as salinity and nutrients were not available.

The south-western rivers have a high turbidity. The mean suspended sediment concentration in Mongla station of Pussur river (see Figure 1-2 for location) is 1200 mg/l during the peak of flood tide whereas during peak of ebb tide, the value is 1500 mg/l. on 08th November, 2002. (Figure 2-3)

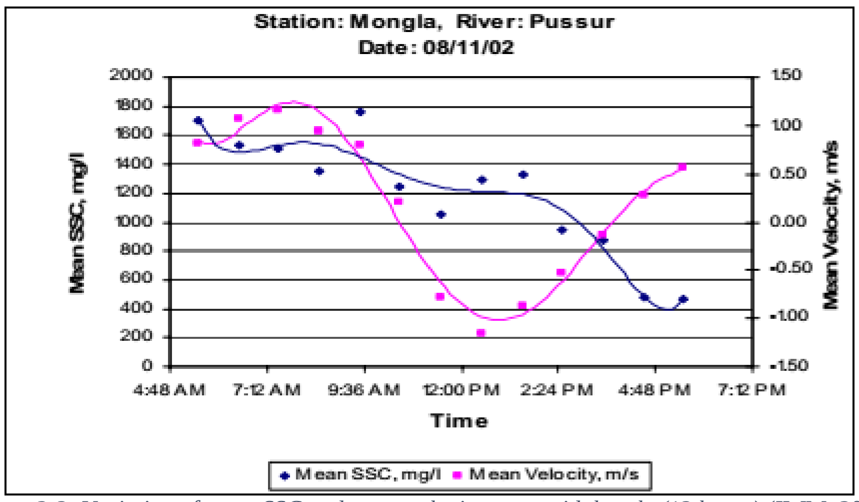


Figure 2-3: Variation of mean SSC and mean velocity over a tidal cycle (13 hours) (IWM, 2003)

CHAPTER 3: Data Collection and Analysis

The quality of research largely depends on the quality of data collected. Data required tocarry out the research is listed in this chapter. Properties of different data collected andtheir sources are described in this chapter.

3.1 Data Collection

The quality of the mathematical model results depends on the quality of the data collected. After anextensive review of literature and considering the research objective of the study, a list ofrelevant data required was prepared. To carry out a study on regional scale morphodynamics with hydrodynamic and advection-dispersion model, the following data are required:

i. River network mapping
ii. The geometrical data of the rivers
iii. Measured river flow data
iv. Measured Water Level Data
v. Measured Velocity Data
vi. Sediment rating curve from measured data
vii. Measured Settling velocity

3.2 River Network

The south-west area of Bangladesh is the study area which is encircled by the Ganges River on the north-west direction (Figure 1-2). The river reach of Ganges is 86 km long before it meets the Jamuna river at Goalanda. It is a major transboundary river which flows along the border between India and Bangladesh ("Ganges," n.d.). The Ganges enters in Bangladesh near Rajshahi city.

Gorai is the main distributary of the Ganges River (see Fig. 3-1). It is the most important source of fresh water for the western part of the study area. The Gorai River forms Madhumati river and Nabaganga River at Bordia. The Madhumati River unites with Baleswar river and falls into the Bay of Bengal. These two rivers acts as the main connectivity to other small rivers.

The Jamuna river is the main distributary channel of the Brahmaputra river (see Fig. 3-1). It is another transboundary river shared by China, India, and Bangladesh. After the confluence of Ganges and Jamuna, the river is named Padma. The Padma river is 79 km long.

The Arial khan river is the main distributary of the Padma River and major fresh water source in the south-eastern part of the study area (see Fig. 3-1). It delivers fresh water to the Baleswar river, Bishkhali river, Buriswar River and Tetulia River. At Chandpur, the river Padma meets with the upper Meghna river and flows downstream as Lower Meghna River which then runs into the Bay of Bengal. The Lower Meghna River has three spills.

The Bay of Bengal is situated on the south direction of the study area. The study has an extension of 42960 km^2 and about 3909 km of river network.

Table 3-1: Important rivers within the study area and their considered lengths

River Name	Length (km)	River Name	Length (km)
GANGES	87	JAMUNA (SW)	62
JAMUNA	148	ARPANGASIA	60
PADMA	80	SIBSA	67
UPPER_MEGHNA	81	MINAJNADI	17
LOWERMEGHNA	92	PUSSUR	98
GORAI	190	KAZIBACHA	15
MADHUMATI	59	RUPSA	17
NABAGANGA (Lower)	29	BALESWAR	52
KALIGANGA	31	BISHKHALI	91
ARIALKHAN	157	BURISWAR	57
TORKI	43	LOHALIA	72
BETNA	89	TENTULIA	90
KOBADAK	244	KIRTONKHOLA	41
BHAIRAB	137	PAIRA	24
MATHABHANGA	165	KOCHA	15
AFRAKHAL	36	MONGLA_NULLA	15
CHITRA	110	M.G.CANAL	8
FATKI RIVER	48	GASHIAKHALI	23
HARIHAR	39	DHULIA	23
MUKTESWARI	32	SHIKARPUR	17
ATAI	14	SWARUPKATI	25
HISNA	44	ILSHA	32
NABAGANGA (Upper)	140	JOYANTI	33
TEKA, HARI, TELIGATI and GENGTREIL	44	AMTALI	13
BHADRA	12	RANGAMATIA	25
GANGES	87	JAMUNA (SW)	62
JAMUNA	148	ARPANGASIA	60
PADMA	80	SIBSA	67
UPPER_MEGHNA	81	MINAJNADI	17
LOWERMEGHNA	92	PUSSUR	98

3.3 The Geometry Data

The geometry of the rivers along with their alignment is required to represent them in the hydrodynamic model. The geometry data that was used in the study area was delivered and utilized in the project "*Living polders: dynamic polder management for sustainable livelihoods, applied to Bangladesh"* financed by the Netherlands Organization of Scientific Research. The examples of of typical cross-section of Jamuna, Meghna (upper) and Pussur river is shown in Figure 3-1 respectively.
Among the rivers that are in the study area, Jamuna is a braided river.

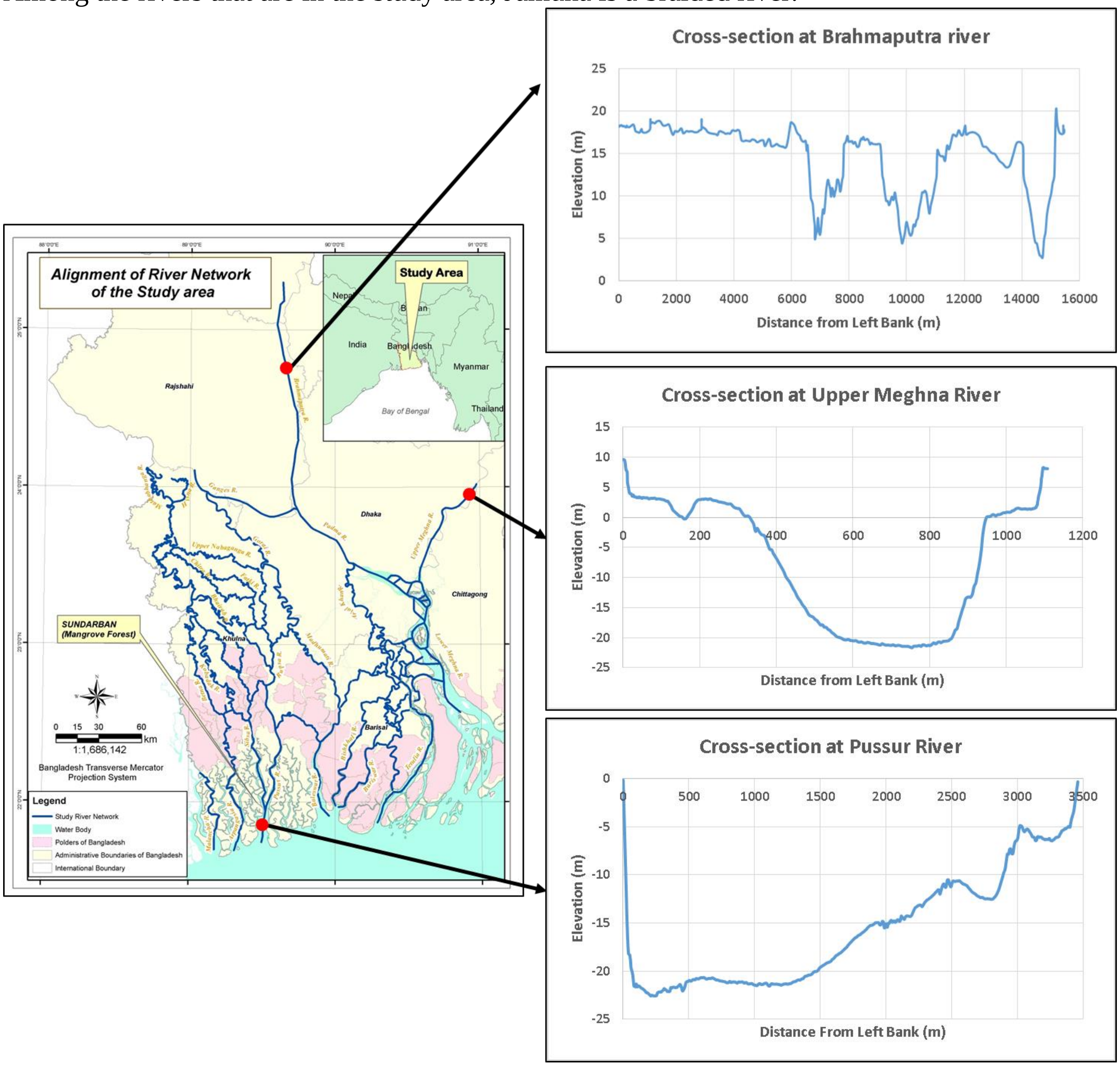


Figure 3-1: Sample cross-sections of Brahmaputra, Upper Meghna and Pussur Rivers.

3.4 Water Level

The observed water levels at various river locations are collected from different sources and delivered by the "*Living polders: dynamic polder management for sustainable livelihoods,*

applied to Bangladesh" project. The water levels are used as downstream boundaries of the hydrodynamic model and for calibration & validation.
The downstream part of the study area has a semidiurnal tide and has a tidal period of 12 hour and 25 minutes. This means that everyday there are two high water and two low waters. The consecutive high or low waters are not of the same height. This is called diurnal inequality (Fig. 3-3).

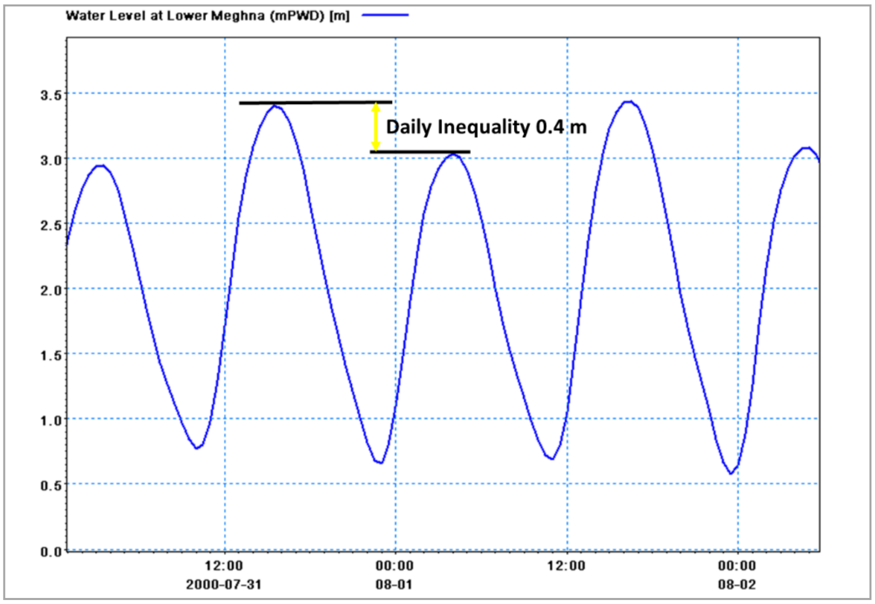


Figure 3-2: Daily inequality in water level

The water level experiences spring and neap tides depending on the position of moon and sun. Every fortnight, when the sun and moon are aligned around times of new or full Moon, the largest tidal ranges in semi-diurnal regions occur during spring tides; while the smallest tidal ranges occur during neap tides, when the Moon and Sun are in quadrature.
There is also a seasonal variation of water level between monsoon and dry (winter) seasons. The seasonal variation is 0.83 m in Charchanga tidal station of Lower Meghna river. This data was taken from the Southwest region hydrodynamic model of IWM to analyze the seasonal variation. In Figure 3-3, the resolution of the data is 30 minutes and the time span of the data is from 1st April, 2000 to 31st March, 2001. The number of data points is 17520.

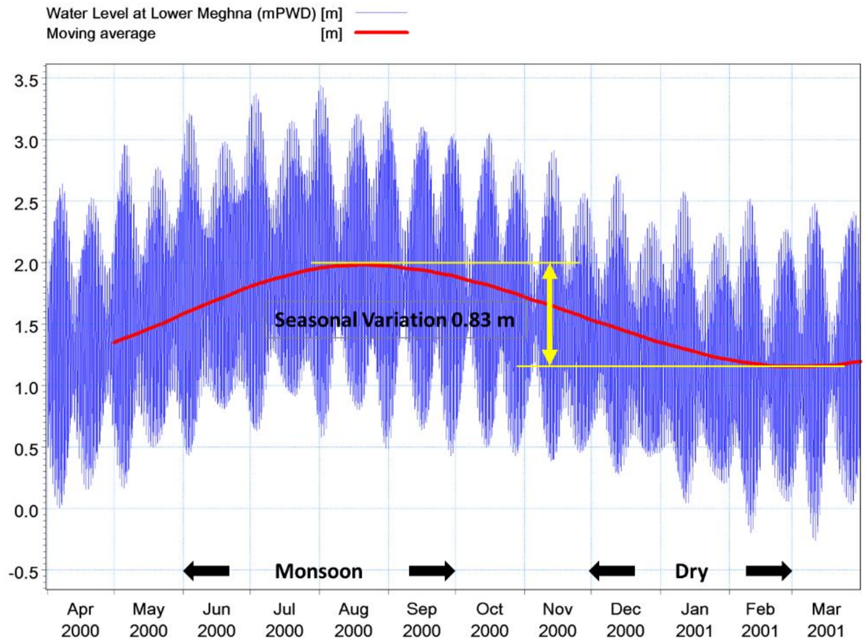


Figure 3-3: Seasonal variation of water level at lower Meghna river

Figure 3-4 shows the tidal time lag between three downstream locations. The data for Location 1, 2 & 3 are obtained from Heron point, Khepupara and Charchanga tidal water level stations, respectively. The figure shows that the time lag between high tides and the time lag between low tides are different. The time lag between location 1 & 3 is 7.5 h during ebb tide and 5 h during the progression of flood tide at location 3. The time lag in location 1 & 3 is 6 hour during low tide. The duration of ebb tide is larger than flood tide at location 3. This tidal asymmetry is typical of shallow water tidal systems.

There is no time lag between location 1 & 2 during high tide; while the time lag is 1 hour during low tide.

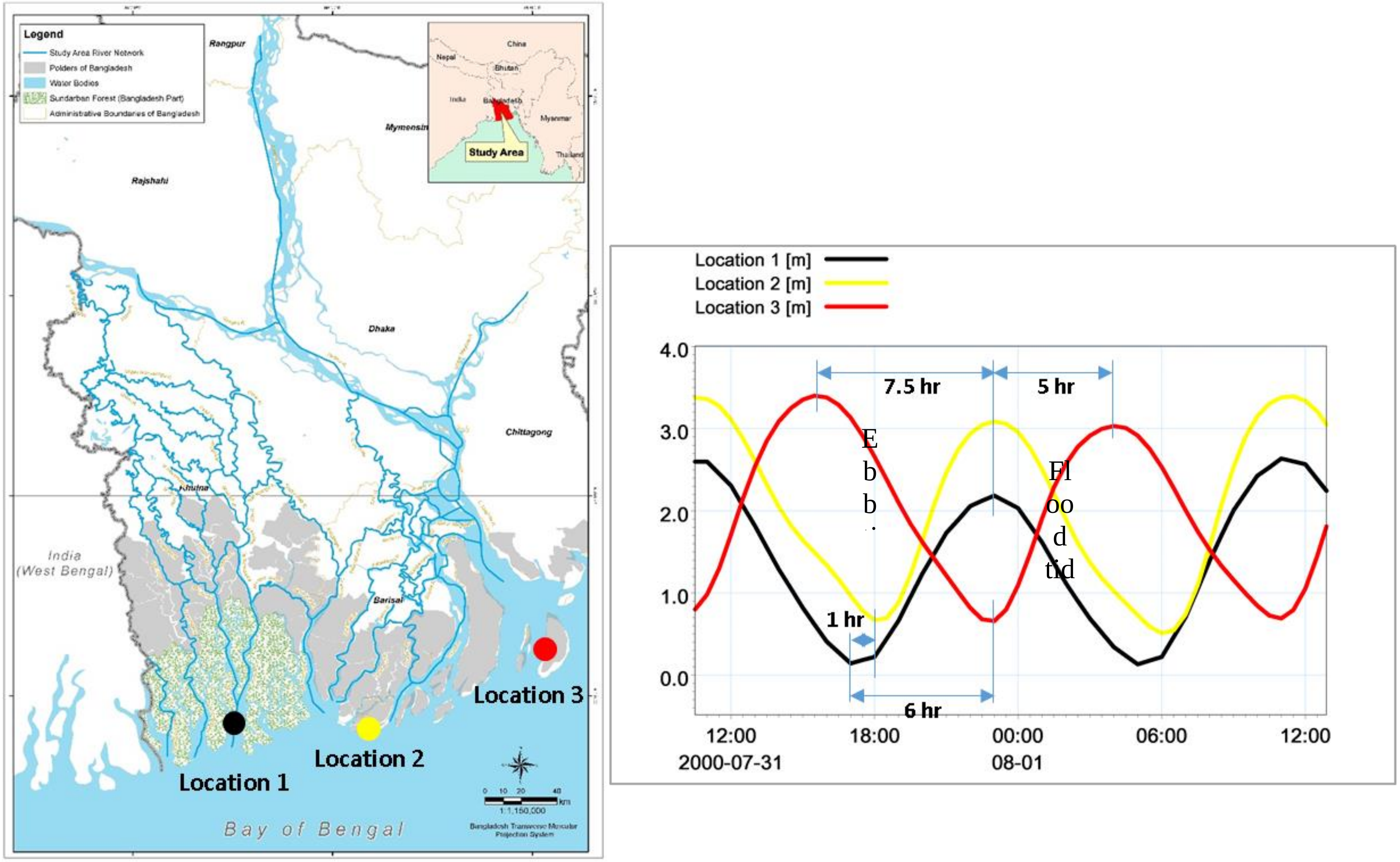


Figure 3-4: Time lag of tides of downstream points

3.5 Discharge

The Ganges and Brahmaputra rivers drain the Himalayan slopes and ranked among the principal water carrying rivers in the world (Islam et al., 1999). The Ganges, Brahmaputra and Meghna had a maximum discharge of 60137 m^3/s, 71907 m^3/s, 17237 m^3/s for the hydrologic year 2000. These data is taken from the Southwest region hydrodynamic model of IWM to analyze the seasonal variations in the discharge values.

All the rivers in the study area have large seasonal variation. The peak discharge occurs in monsoon (June-September) and the lowest discharge occurs in the pre-monsoon season (March-May). The river discharge also has interannual variations related to temperature and precipitation.

Table 3-2: Discharge values of three Principal rivers for the year 2000

River name	Maximum flow (m^3/s)	Minimum flow (m^3/s)	Average flow (m^3/s)
Ganges	60137 (24th September, 2000)	546 (29th March, 2001)	13698
Brahmaputra	71900 (6th august)	3184 (25th March)	22920
Meghna	17237 (20th august)	450 (21th March)	6485

3.6 Seasonal Variation

The water level, flow discharge and sediment discharge vary widely in the Ganges-Brahmaputra-Meghna delta according to the seasons. In the base year 2000, the Brahmaputra river had a flow discharge of 3184 m^3/s at march (pre-monsoon), a peak flood discharge of 71900 m^3/s at August (monsoon) and 9000 m^3/s at November (post-monsoon) (Figure 3-5). The river Ganges and Meghna also had a similarly large seasonal variation of flow.

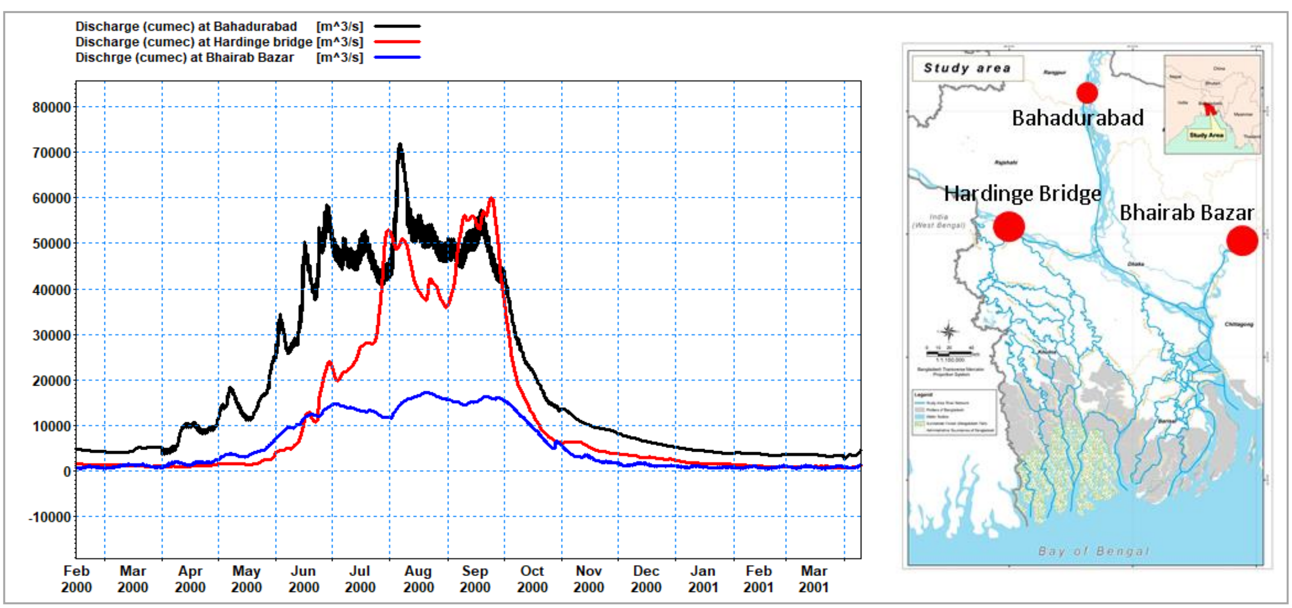


Figure 3-5: Measured flow discharge at the three upstream boundaries (Bahadurabad, Harding Bridge and Bhairab Bazar) in Jamuna, Ganges and Upper Meghna respectively.

The sediment transported by these three mighty rivers depends largely on the seasonal variation. The highest and the lowest monthly sediment transports are 334.2 million tons and 4 million tons, respectively. For the Ganges the highest SSC is about 1600 mg/1 and for the Jamuna it is 1400 mg/1, while the lowest is 190 mg/1 for the Ganges and 220 mg/1 for the Jamuna (Barua, 1990).

3.7 Tidal Pattern

Tides in the northern Bay of Bengal are predominantly semidiurnal and have a mesotidal amplitude range (Henry and Murty, 1982).

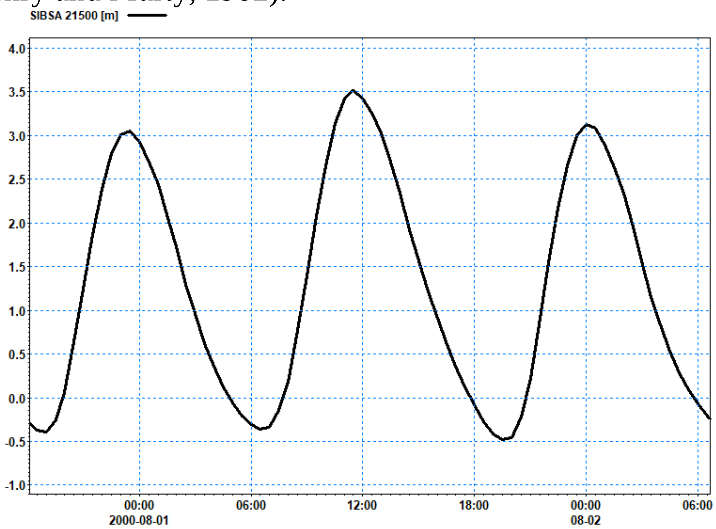


Figure 3-6: Semi-diurnal tides at Sibsa river

The Meghna estuary is micro-tidal. Differences in tidal range are important, as they are often related to variations in coastal processes and morphology.

3.1 Settling velocity

The settling velocity is a very important parameter to understand the dynamics of cohesive sediment.

The value of settling velocity has been considered same in all of the study area for both monsoon and dry season due to unavailability of measured data. In the Sundarbans Biodiversity project (IWM, 2003), measured data of settling velocity is available in the rivers inside Sundarbans (Table 3-3). The low values of settling velocity suggests the transport of sediment in suspension. The settling velocity data were measured during the discharge observations for a full tidal cycle (13 hours).

Table 3-3: Settling velocity of the sediments presented by Sundarbans Biodiversity Project ((IWM, 2003)

Station Name	**River Name**	**Date**	**Average Settling Velocity (mm/s)**	
			Ebb Tide	**Flood Tide**
Arpangasia	Arpangasia	02.12.2001	0.06	0.04
Digraj	Pussur	13.01.2001	0.16	0.21
Digraj	Pussur	16.10.2001	0.24	0.77
Dingimari	Jamuna (SW)	30.11.2001	0.03	-
Kobadak	Kholapetua	01.03.2001	0.08	0.06
Malancha	Malancha	01.12.2001	0.22	0.05
Nalianala	Sibsa	27.02.2001	0.16	0.12

CHAPTER 4: Development of Cohesive Sediment Transport Model

4.1 Hydrodynamic Model

1D hydrodynamic model incorporating the river inside the study area, were developed from the south-west regional model (SWRM) of Institute of Water Modelling. The southwest regional model covers about 5600 km length of rivers which includes almost all small and large rivers of south-west Bangladesh. But this was a hindrance for developing the cohesive sediment transport model as the SWRM model has about 2295 h-grid points (h- elevation) and about 2266 Q-grid points (Q -water flow) for calculation. The large model was also posing problem to understand the dynamics of the rivers in consideration of a regional scale. The boundary conditions for sediment discharge was not readily available which also prompted to reduce the number of boundaries in the developed model. In other words, it was very important to simply the network of the model to reduce the calculated grid points and be able to develop the cohesive sediment transport model finally.

The space between the cross sections is an important factor for stability of mathematical model computation. An adequate spacing between consecutive cross-sections ensures the stability of the mathematical model. Cross sections placed too far apart can cause numerical damping of the water level. Cross sections placed too close together can cause wave steepening and model instability on the rising side of the flood wave. The maximum spacing between the cross section was 10000 m (آدینه, 1394). The stability of the Mike 11 HD model was defined by Courant number. The following equation specifies the maximal allowed courant number depending on the grid size and time step.

$$Cr = \frac{(v + \sqrt{gD})\Delta t}{\Delta x}$$

Where,

Δx = maximum spacing between cross-sections

Δt = the integration time step of the HD model

v = mean velocity of the cross-section

D = Hydraulic depth of the cross section

The roughness of the cross section is one of the parameters which controls the flow velocity. The cross section only covered rivers and the flood plains are not included.

Chow (1959) indicates that the value of n is highly variable and depends on a number of factors: (1) surface roughness; (2) height, density, distribution and type of vegetation; (3) channel irregularity which comprises irregularities in wetted perimeter and variations in cross section, size and shape along the channel length; (4) channel alignment; (5) silting and scouring; silting may decrease n, whereas scouring may increase n (6) obstructions, like the presence of bridge piers tends to increase n; (7) size and shape of channel; and (8) stage and discharge.

The sediment size such as sand will result in a relatively low value of n and coarse sediments such as gravels, in a high value of n; The median grain size (D_{50}) found at the lower Meghna estuary was 120 micrometer (Ahmed & Louters, 1997). An increase in hydraulic radius may either increase or decrease n depending on the condition of the channel and n value in most streams decreases with increase in stage and discharge. However, the n value may be large at high stages if the banks are rough and grassy (Ghani et al., 2007). Chow also suggested values of n in a table where three values (minimum, normal, maximum) of n are given for each kind of channel. Table 4-1 gives values of n from Chow (1959) relevant to the present study.

Table 4-1: Suggested Manning n for natural streams (Chow, 1959).

Type of channel and description	Minimum	Normal	Maximum
Stream on plain	0.025	0.03	0.033
Clean, straight, full stage, no rifts or deep pools			
Same as above, but more stones and weeds	0.030	0.035	0.04
Clean, winding, some pools and shoals	0.033	0.04	0.045
Same as above, but more stones and weeds	0.035	0.045	0.05
Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
Clean, winding, some pools and shoals, weeds and more stones	0.045	0.05	0.06

No structures were added in the hydrodynamic model because of the data inaccuracy and unavailability.

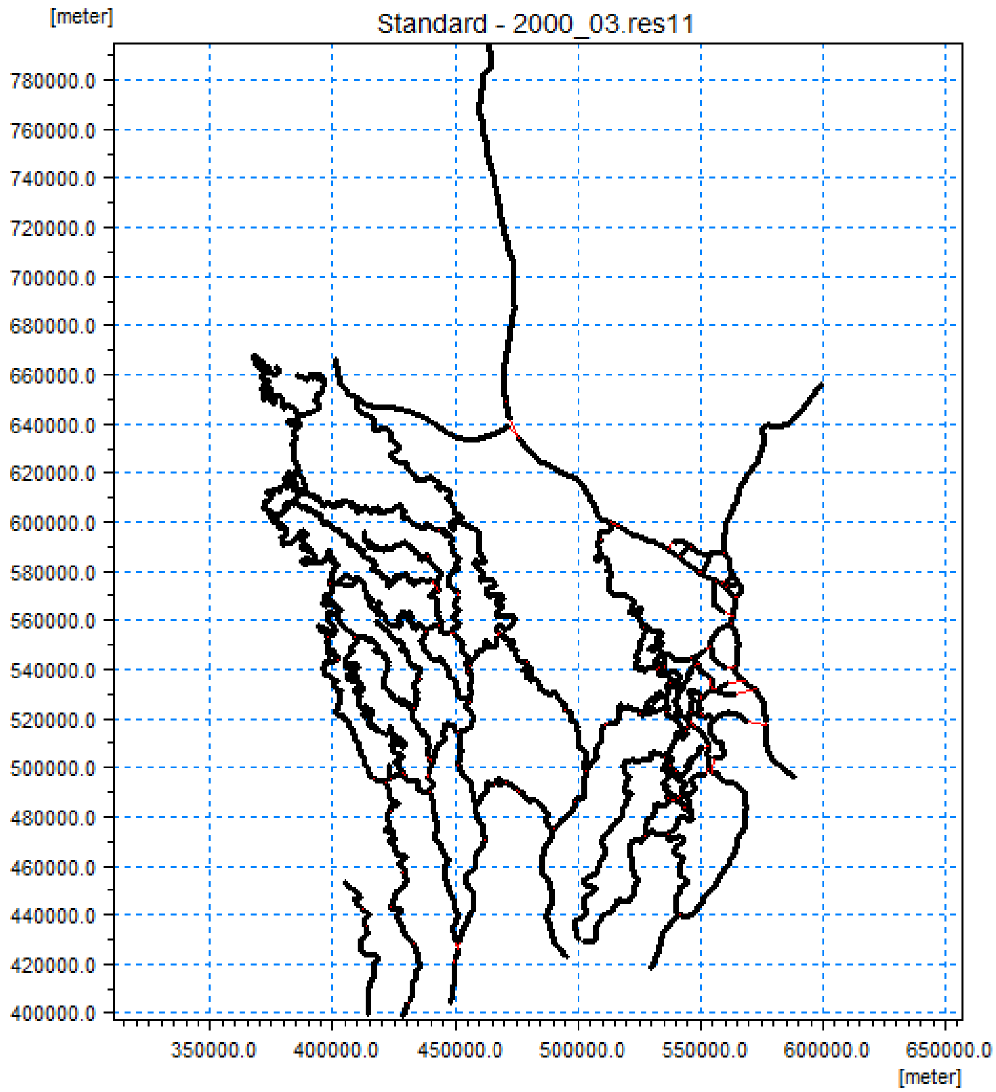


Figure 4-1: The 1D model of the study area (The red lines indicates the junction location between two river reaches)

4.1.1 Calibration

Calibration is a process which requires the adjustment of certain model parameters to achieve the best performance of the model for specific locations and applications (Williams & Esteves, 2017). The hydrodynamic model was calibrated by changing Manning's roughness coefficient, n as model calibration parameters.

Based on availability of observed water level data, the stations of Mawa, Madaripur, Gorai railway bridge, Khulna and Mongla were selected for calibration. To calibrate the water discharge, the stations of Baruria and Kamarkhali are selected along the river Padma and Gorai, respectively. The details of the locations are presented in Table 4-2 and Figure 4-2. The model was calibrated for the monsoon season (June-September) of 2005. The model has also a good agreement between observed and simulated data for pre-monsoon season (march-may).

Table 4-2: Calibration Location for Hydrodynamic model

Serial No.	Station name	River name	Longitude (deg.)	Latitude (deg.)	Calibration
1	Mawa	Padma	90.260	23.470	Water Level
2	Madaripur	Arialkhan	90.213	23.187	"
3	Gorai Railway Bridge	Gorai	89.186	23.884	"
4	Khulna	Rupsa	89.576	22.819	"
5	Mongla	Passur	89.598	22.464	"
6	Baruria	Padma	89.799	23.800	Discharge
7	Kamarkhali	Gorai	89.525	23.527	"

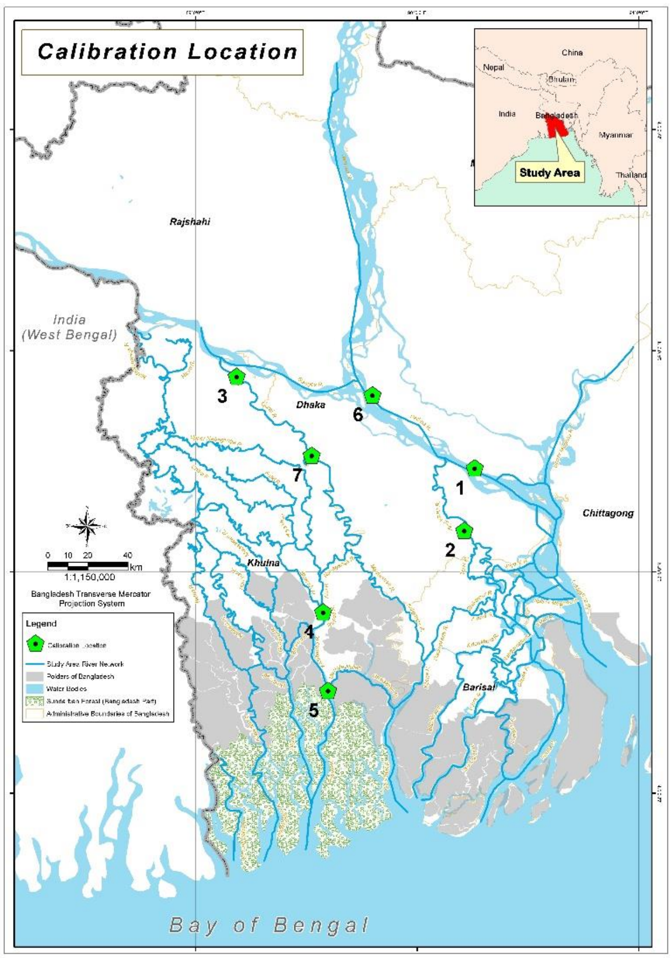


Figure 4-2: Calibration Location for Hydrodynamic model (The number corresponds to Table 4-2

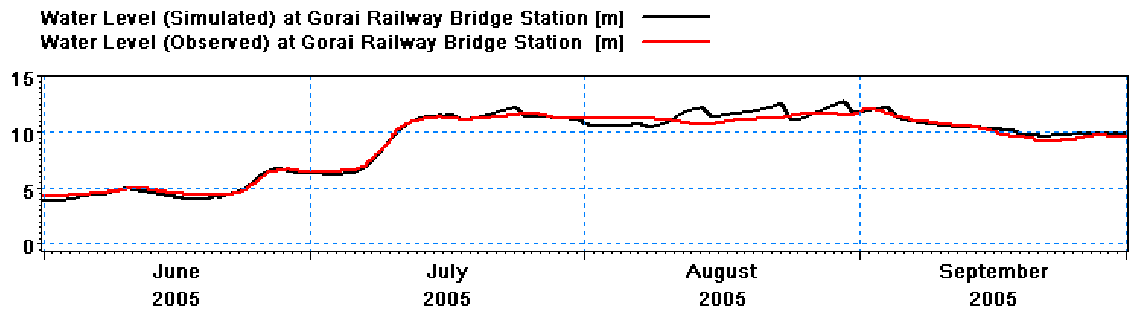


Figure 4-3: Calibration Plot for water level at railway bridge station

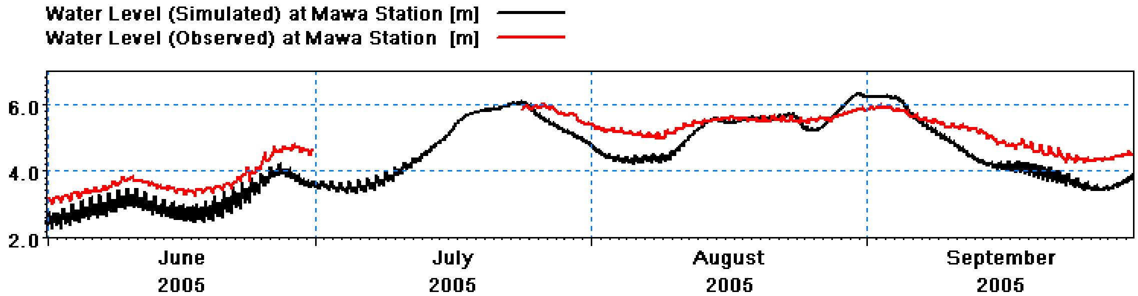


Figure 4-4: Calibration Plot for water level at Mawa Station

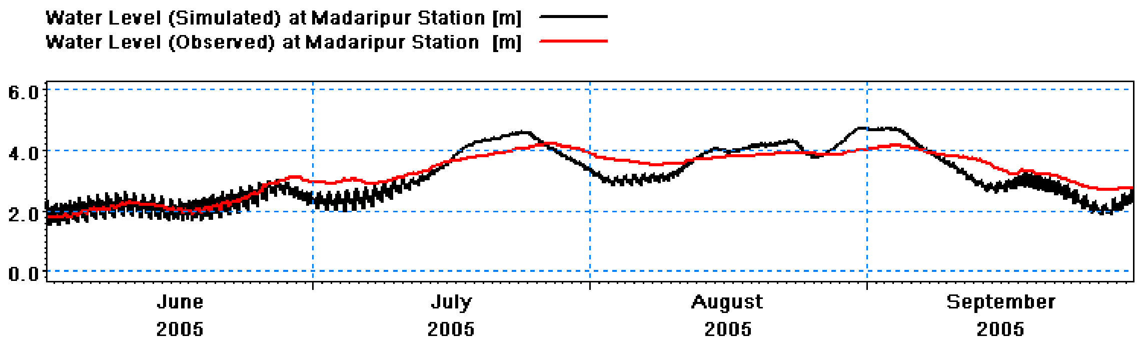


Figure 4-5: Calibration Plot for water level at Madaripur Station

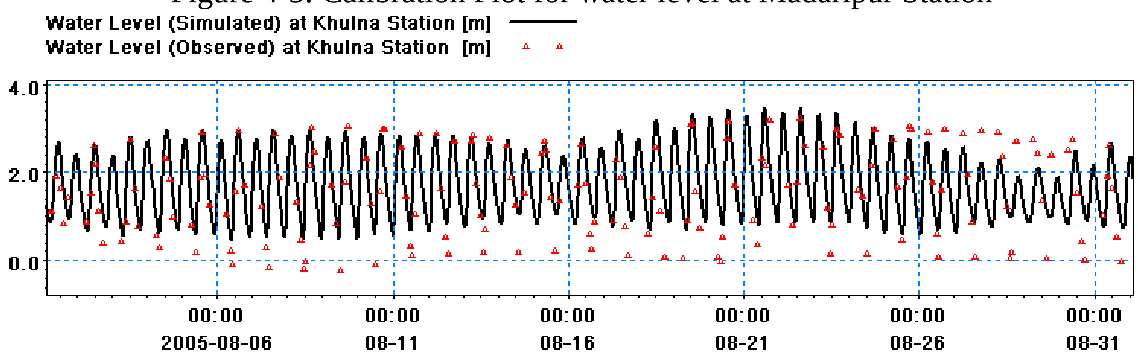


Figure 4-6: Calibration Plot for water level at Khulna Station

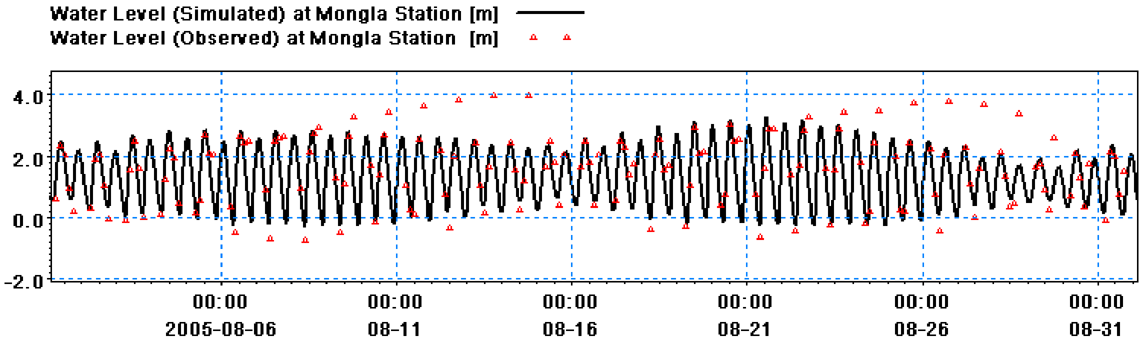


Figure 4-7: Calibration Plot for water level at Mongla Station

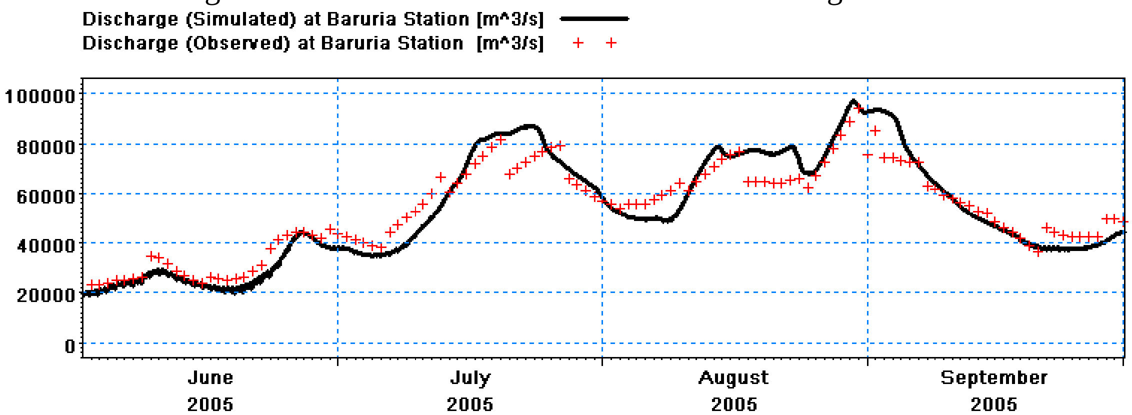


Figure 4-8: Calibration Plot for Discharge at Baruria Station

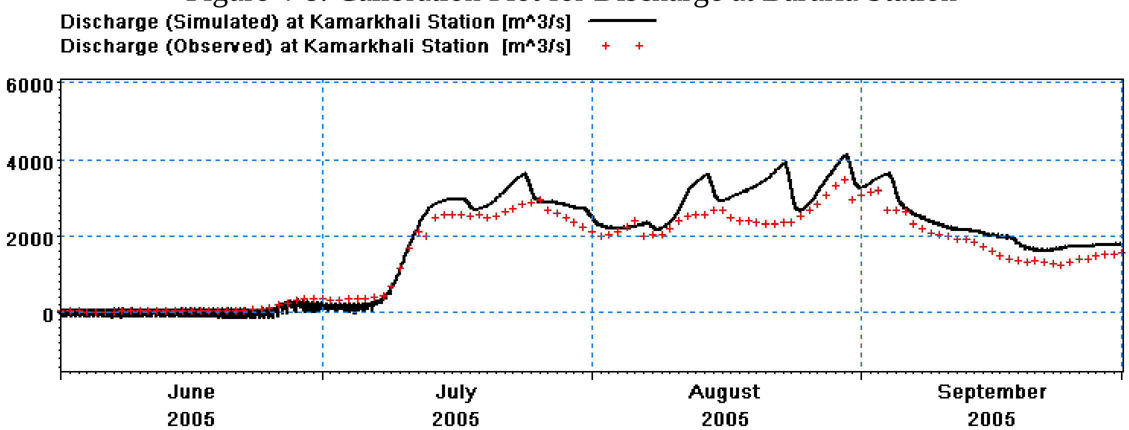


Figure 4-9: Calibration Plot for Discharge at Kamarkhali Station

4.1.2 Validation

According to ("Model validation - Coastal Wiki," n.d.), "Model validation is the formal confirmation of the model quality criteria achieved in model calibration. For model validation a set of independent data is used and the model forcing and model parameters are fixed"

The hydrodynamic model was validated for water level of the year 1999, and for discharge, the model was validated in the year 2008. The set of stations chosen for validation is provided in Table 4-3 and shown in Figure 4-10.

Table 4-3: Validation locations for the hydrodynamic model

Serial No.	Station name	River name	Longitude (deg)	Latitude (deg)	Validation
1	Baruria	Padma	89.799	23.800	Water Level
2	Nalianala	Sibsa	89.422	22.457	"
3	Patharghata	Bishkhali	89.978	22.037	"
4	Gorai Rly.Bridge	Gorai-Madhumoti	89.186	23.884	Discharge
5	Mawa	Padma	90.260	23.470	"

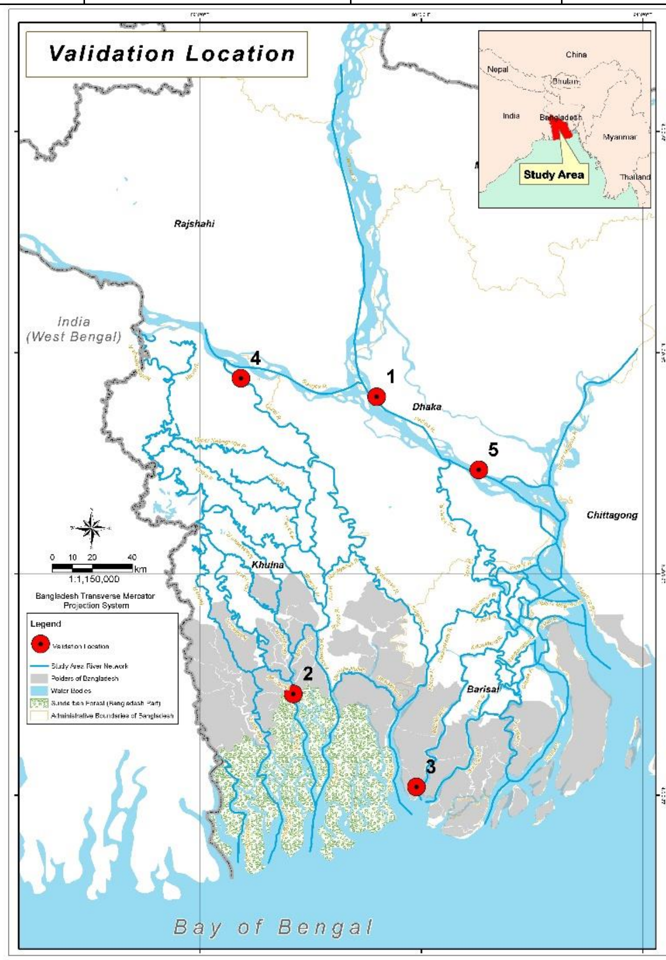


Figure 4-10: Validation location for the hydrodynamic model (The numbers corresponds to Table 4-3)

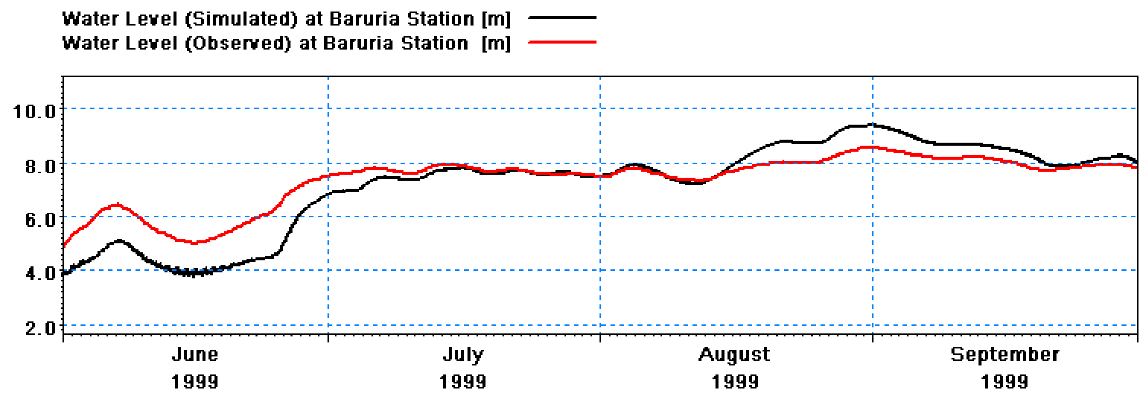


Figure 4-11: Validation Plot for water level at Baruria station

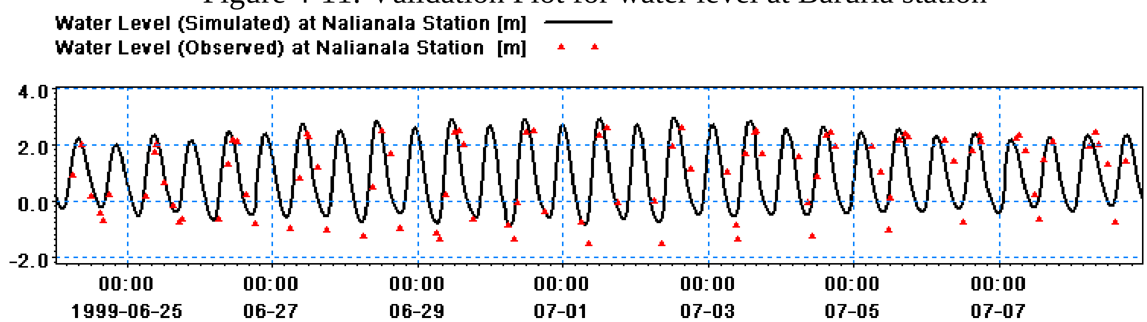


Figure 4-12: Validation Plot for water level at Nalianala station

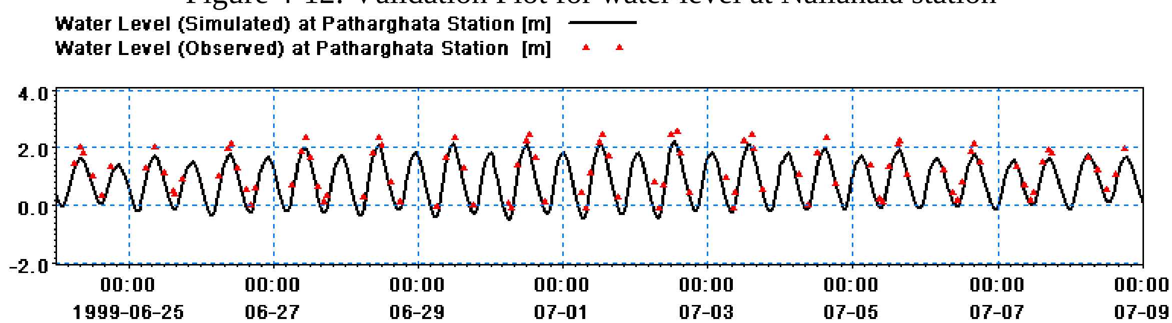


Figure 4-13: Validation Plot for water level at Patharghata station

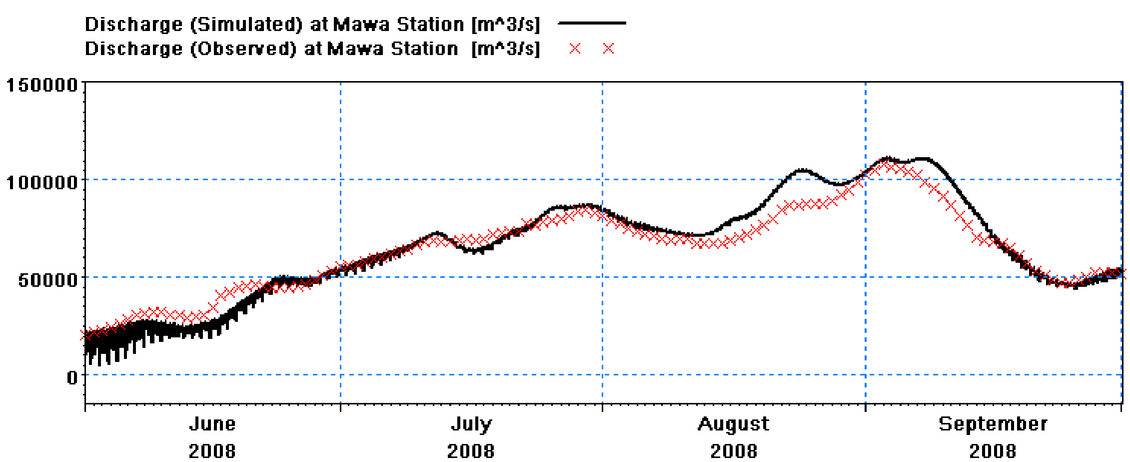


Figure 4-14: Validation Plot for Discharge at Mawa Station

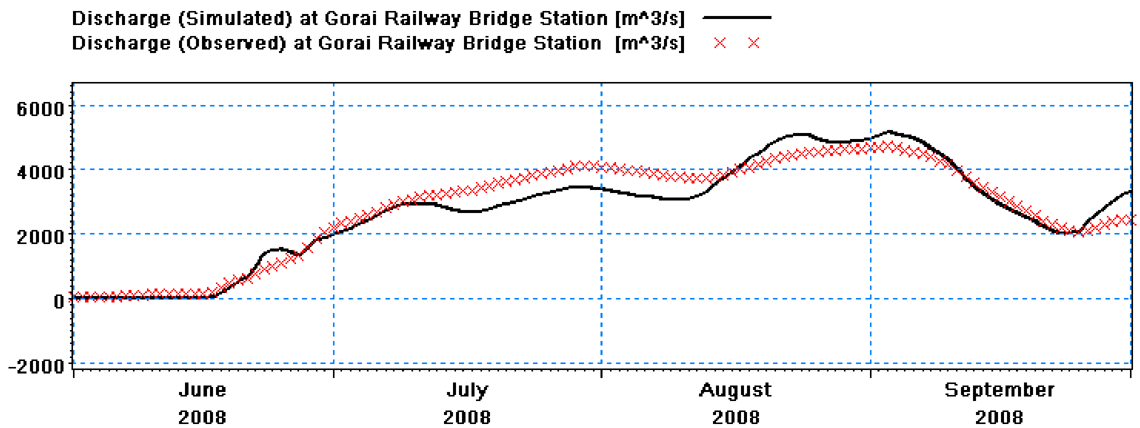


Figure 4-15: Validation Plot for Discharge at Gorai Railway Bridge Station

4.1.3 Error Calculation

Mean absolute (MAE) and root mean square (RMSE) errors are calculated to compare the modelled and observed water surface elevation and discharge for the observed data of both calibration and validation. The calculations for water level are presented in Table 4-4 and for discharge in Table 4-5. Model accuracy is also evaluated using the coefficient of determination or R^2 value.

The RMSE gives a relatively high weight to large errors. The MAE measures the average magnitude of the errors of the dataset. They are used together to diagnose the variation of the errors. The RMSE values are larger than the MAE values. The coefficient of determination parameter takes into account the modelled (Y_{mod}) and observed (Y_{obs}) deviations around the observed mean ($\overline{Y_{obs}}$) to estimate model performance, and varies between 0 (no agreement) and 1 (perfect agreement). The equations for RMSE, MAE and R^2 are as follows:

$$RMSE = \sqrt{\frac{\sum(|Y_{obs} - Y_{mod}|^2)}{n}}$$

$$MAE = \frac{\sum(|Y_{obs} - Y_{mod}|)}{n}$$

$$R^2 = 1 - \frac{\sum(Y_{obs} - Y_{mod})^2}{\sum(|Y_{obs} - \overline{Y_{obs}}|^2)}$$

All calculations are presented in Table 4-4. All the error calculations were done for the full year of 2005 irrespective of the season. The stations used for validation are shown in Figure 4-10.

Table 4-4: Error Calculation for the Water Level

	Station Name	RMSE	MAE	R^2
Calibration (2005)	Gorai Railway Bridge	0.48	0.39	0.98
	Mawa	0.49	0.39	0.90
	Madaripur	0.44	0.38	0.87
	Khulna	0.57	0.44	0.57
	Mongla	0.66	0.43	0.60
Validation (1999)	Baruria	0.70	0.57	0.95
	Nalianala	0.74	0.61	0.63
	Patharghata	0.34	0.27	0.91

Table 4-5: Error Calculation for the Discharge

	Station Name	RMSE	MAE	R^2
Calibration (2005)	Kamarkhali	258.46	157.53	0.98
	Baruria	5003.44	3644.81	0.95
Validation (2008)	Gorai Railway Bridge	306.84	226.36	0.96
	Mawa	5466.73	4455.56	0.97

The difference between RMSE and MAE are larger for Mongla Station. The R^2 values are close to 1 except for Khulna, Mongla and Nalianala station.

4.2 Cohesive Sediment Transport Model

To understand the regional distribution of turbidity maxima, an advection-dispersion model was developed for cohesive sediment of the southwest of Bangladesh.

4.2.1 Model Setup

The advection-dispersion module of Mike 11 software was used to simulate the transport of cohesive suspended sediment. The advection-dispersion (AD) module is based on the one-dimensional equation of conservation of mass of a dissolved or suspended material, i.e. the advection-dispersion equation. The module requires output from the hydrodynamic module, in time and space, in terms of discharge and water level, cross-sectional area and hydraulic radius. The Advection-Dispersion Equation is solved numerically using an implicit finite difference scheme which, in principle, is unconditionally stable and has negligible numerical dispersion. The one-dimensional (vertically and laterally integrated) equation for the conservation of mass of a substance in a solution, i.e. the one-dimensional advection-dispersion equation reads:

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) = -AKC + C_2 q$$

Where,

C: concentration, D: dispersion coefficient, A: cross-sectional area, K: linear decay coefficient,
C_2: source/sink concentration, q: lateral inflow, x: space coordinate, t: time coordinate

4.2.2 River Network for Advection-Dispersion Model

The river network was made smaller for the simulation of advection-dispersion model than from the network of hydrodynamic model. The river reaches, in which no tidal movement was not seen, was detracted from the model to reduce the calculation points and to reduce the simulation time. The maximum spacing of cross-sections was adjusted to fulfill the criteria of Courant number less than 1.

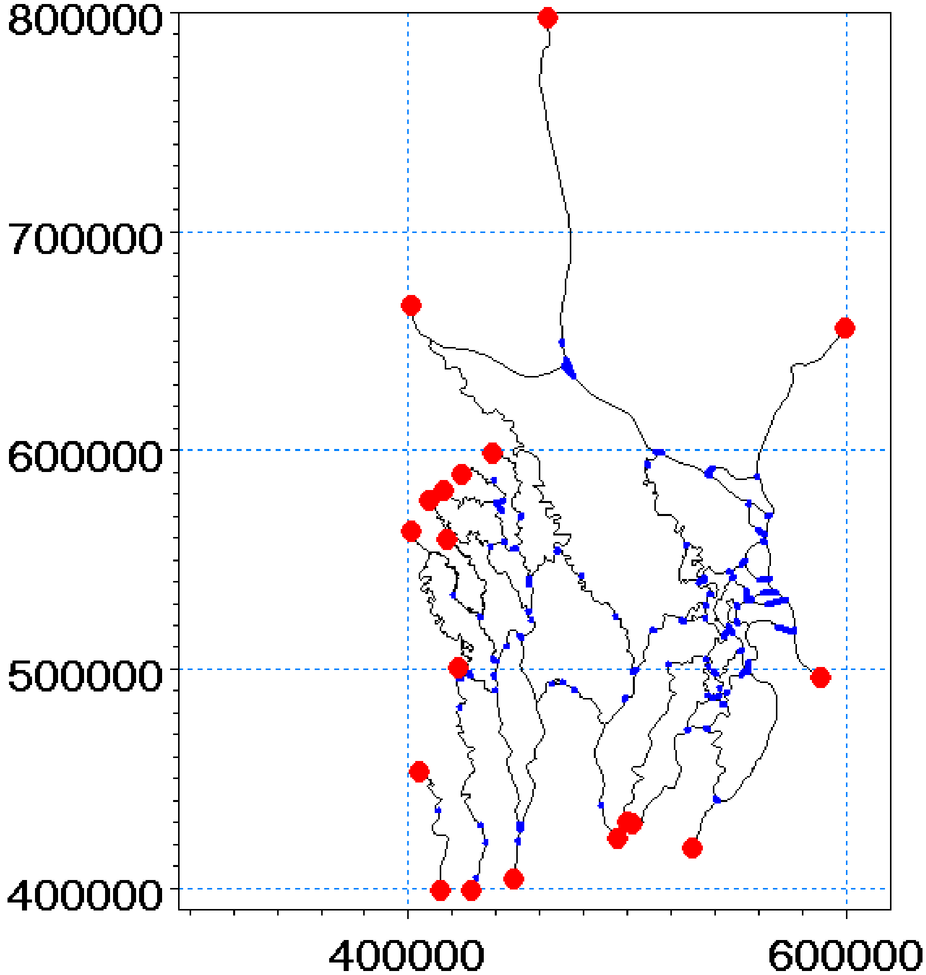


Figure 4-16: River network of the advection-dispersion model (Red points are the upstream and downstream boundaries and blue lines are the junctions of two or more river reaches)

4.3 Sediment Rating Curve

To develop the cohesive sediment transport model, sediment concentration is required as boundary condition. As measured data were not available for the simulation period in line with the developed hydrodynamic model, the sediment rating curves were utilized for generating these boundary conditions. These sediment rating curves were either collected from different reports and published papers or generated from measured data of different time frames through trend line analysis between water discharge and velocity and measured suspended sediment concentration. These generated SSC boundary data were used, although some of the generated curves had low R^2. (see Figures 4-17 to 4-20)

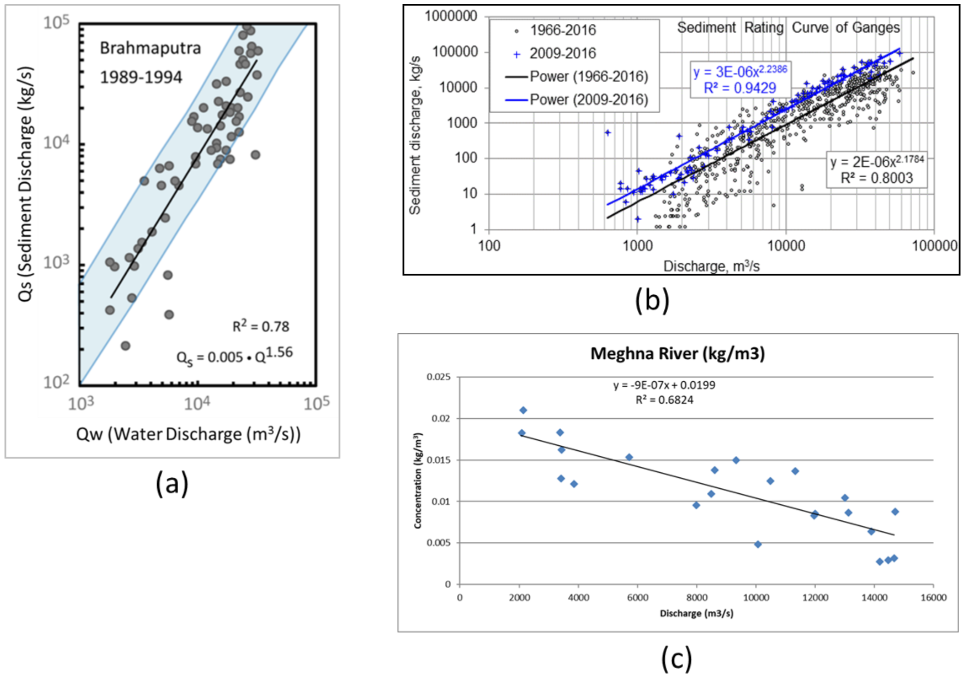


Figure 4-17: Sediment Rating Curve for (a) Brahmaputra; (b) Ganges; (c) Upper Meghna River

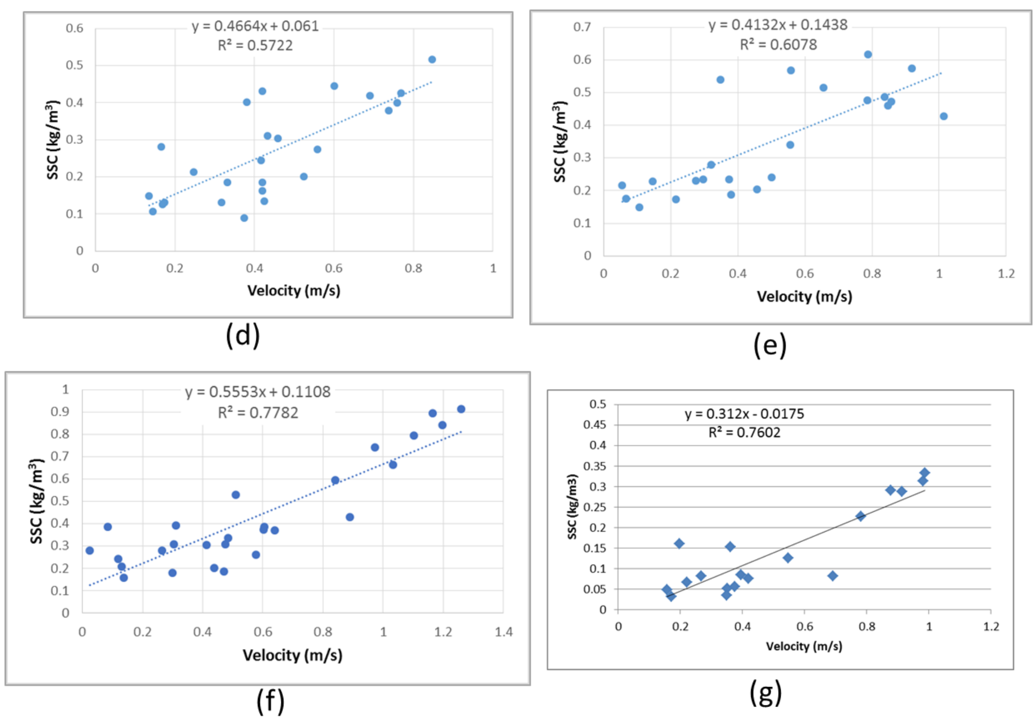


Figure 4-18: Sediment Rating Curve for (d) Jamuna (SW); (e) Malancha; (f) Pussur; (g) Baleswar River

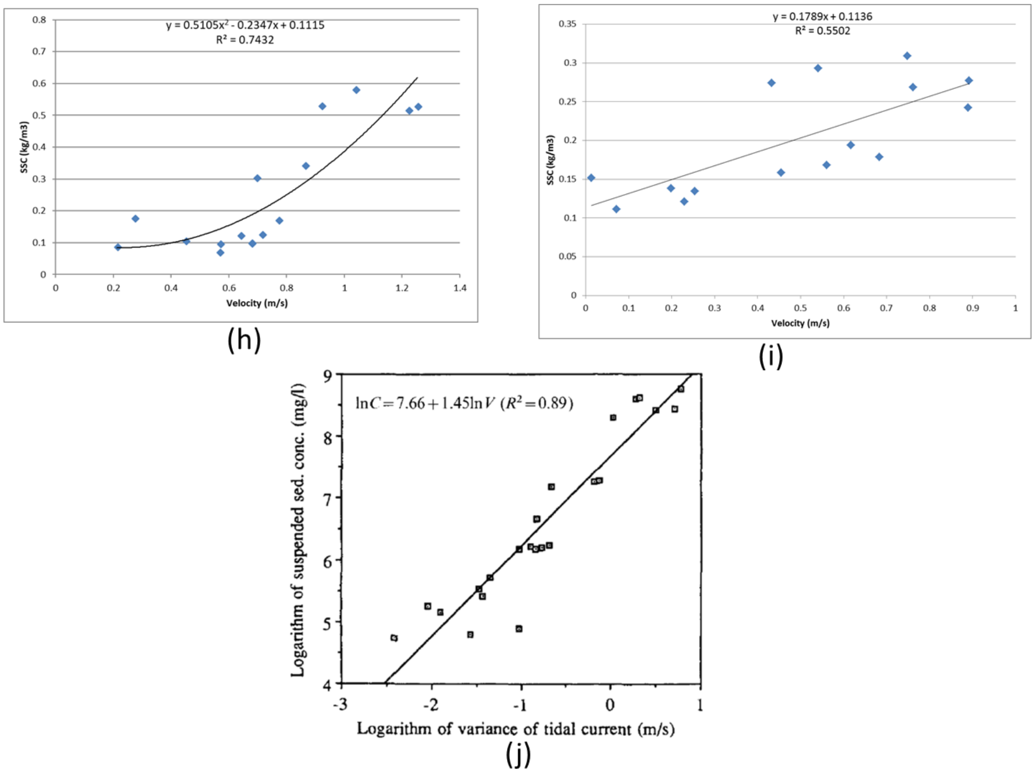


Figure 4-19: Sediment Rating Curve for (h) Bishkhali; (i) Buriswar; (j) Tetulia and Meghna (Lower) River

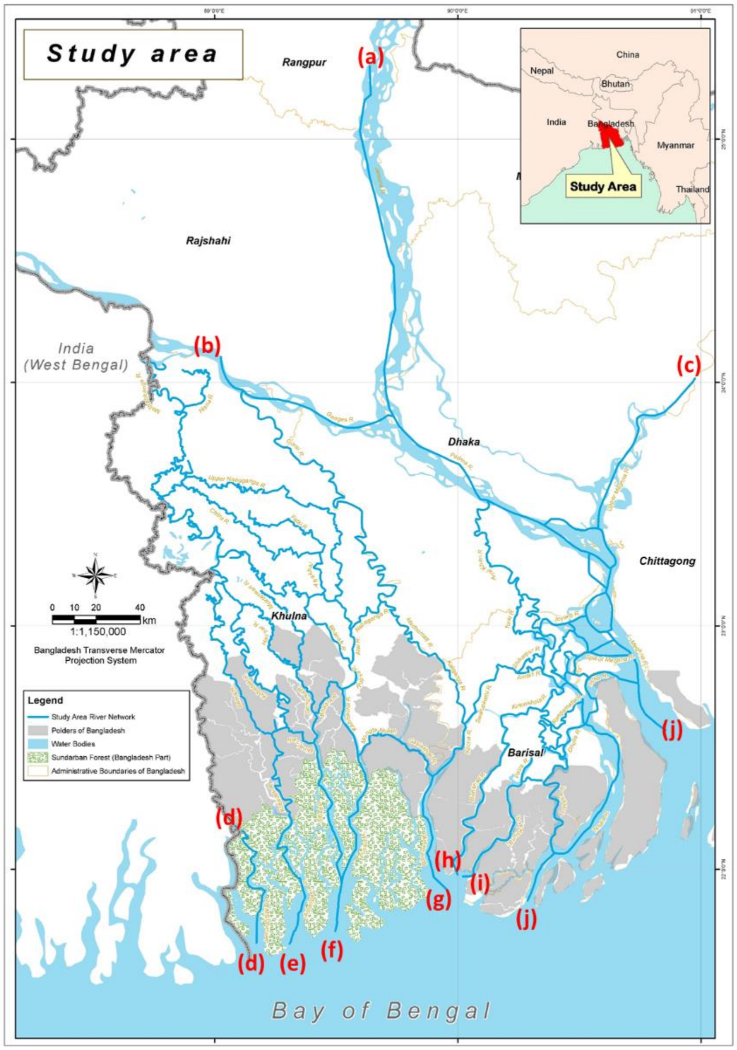


Figure 4-20: The locations for the seddiment rating curves generated (refer to Figure 4-17, Figure 4-18, Figure 4-19)

CHAPTER 5: Results

The developed hydrodynamic and cohesive sediment transport model was simulated for different scenarios. The results of simulated model are presented in this chapter.

5.1 Variation of Tidal Range for the Base Year (2000), Dry Year (2001) and Flood Year)2004).

Tidal range is the vertical difference in height between consecutive high and low waters over a tidal cycle (Surgewatch.org, 2018) The range of the tide varies between locations and also varies over a range of time scales. Differences in tidal range are important, as they are often related to variations in coastal processes and morphology. The tidal ranges higher than 0.25 m is considered in the following analysis.

In the monsoon season of the year 2000 (Figure 5-1), the tidal range increases upstream along the rivers of the western part of the study area, reaching a maximum of about 4.3 m in the north boundary of the Sundarbans. Afterwards the tidal range gradually decreases further north, and the tidal influence becomes negligible (tidal range < 0.25 m). The tidal influence is perceptible as far as 120 km upstream the Betna river (Western part of the study area). The tidal influence extends further north as we move to the east in our study area.. In the Arpangasia-Kobadak (lower) river sytem, the tidal range increases from 2.6 to 4.3 m (south to north). In the Sibsa river, the value increases from 3.1 to 4 m (south to north).

In the eastern part of the study area (Figure 5-1), the tidal range gradually decreases upstream the rivers.

In the Meghna (lower) river, the tidal range decreases from 2.7 m to 0.6m at Chandpur. The Meghna (lower) river has three spills which connects t it to the eastern part of the study area (refer to Figure 1-2) In Joyanti river (spill-1), the tidal range changes from 0.9 m to 0.3 m. In Ilsha river (spill-3), the tidal range is about 1.7 m. In spill-2, the value is about 1.2 m.

In the arial khan river, the tidal range is 0.3 m. In the Madhumati river, the tidal range is 0.3 m at Bordia. There is no tides in Gorai river.

In the pre-monsoon season of year 2000 (Figure 5-4), the tidal ranges depict a similar spatial pattern as in the monsoon season. Some differences are found at Sibsa, Kobadak (lower) at the north boundary of the Sundarbans. In the Sibsa river, the tidal range increases up to 4.4 m. In the Arpangasia-kobadak river system, the tidal range increases up to 4.6 m. it is remarkable also that the tidal influence now extends up to the junction with Ganges along the Gorai river (more than 350 km upstream).

The Padma, Meghna (upper), Gorai, Arial Khan, has considerable changes in tidal range The Padma river has tides of 0.9m to 0.6 m of tidal range. The Meghna (upper) river has tidal range of 1.25 m. The arial Khan river has tidal range of 0.68 m. In the Madhumati river, the tidal range increases by 1.0 m at Bordia. . The Gorai river has tidal range of 1.5 m to 0.25 m.

In the Meghna (lower) river, the tidal range decreases from 2.17 m to 1.3m. In the spills of the Meghna (lower) the tidal range increased by 0.8 m.

In the post-monsoon season of year 2000 (refer to Figure 5-5), The tidal ranges are same in all of the study area, In case of Gorai river, The tide advances landward more than monsoon season but less than pre-monsoon season.

In the dry monsoon of 2001 (refer to Figure 5-2), There is evident changes in Sibsa river at the north boundary of Sundarbans. The Gorai river has tides 0.25-0.5 m as the Gorai river has less flow than base year.

The pre-monsoon and post-monsoon of the dry year are the same as the base year.

In the monsoon of the flood year (2004), The tidal boundary pushed seaward. The Spill of Meghna has tides of 0.25-0.5 m. At the north boundary of the Sundarbans, the Sibsa has tidal ranges of 4.0 m; which is exceptional.

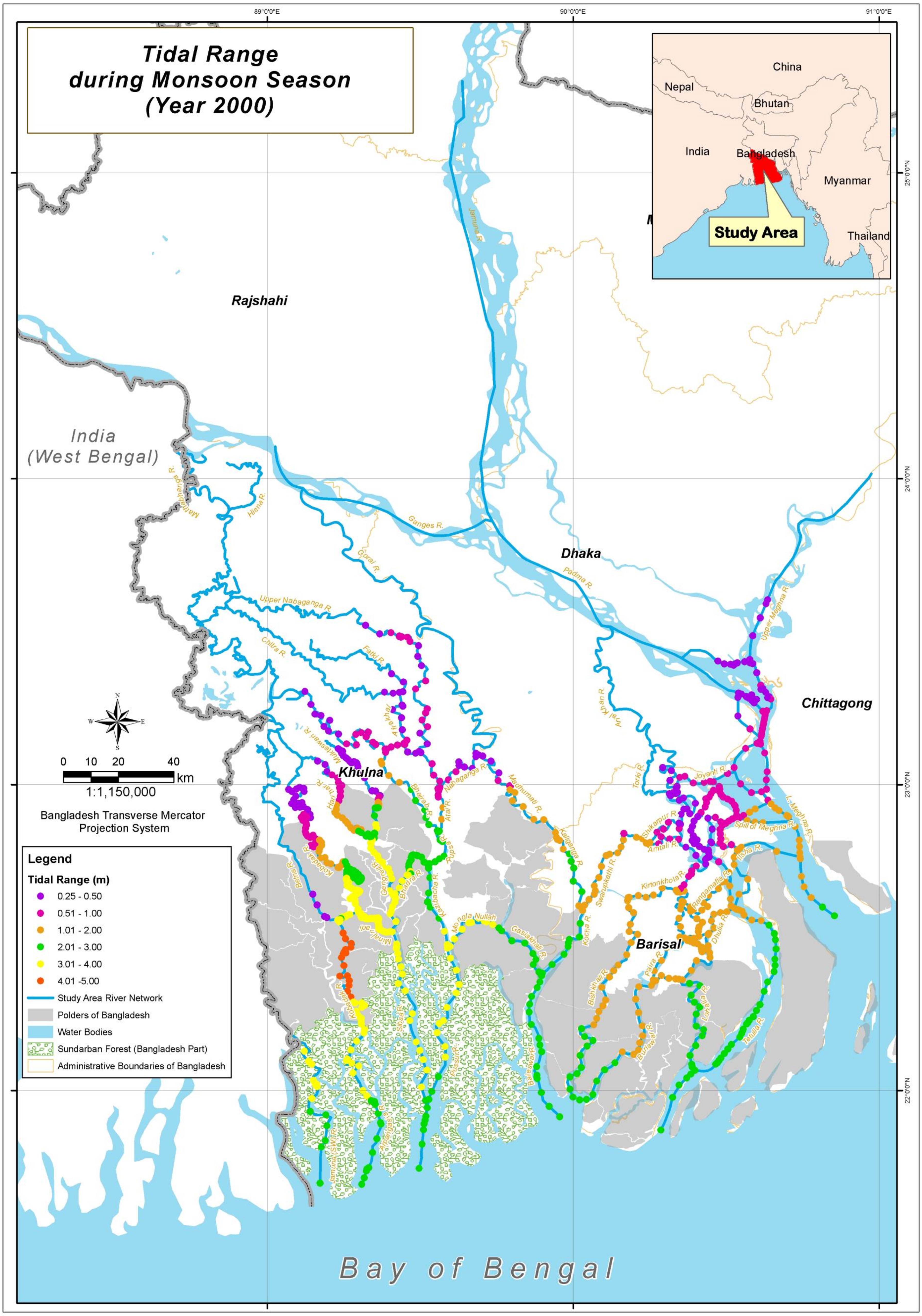


Figure 5-1: Tidal Range along the rivers in the Monsoon Season, year 2000

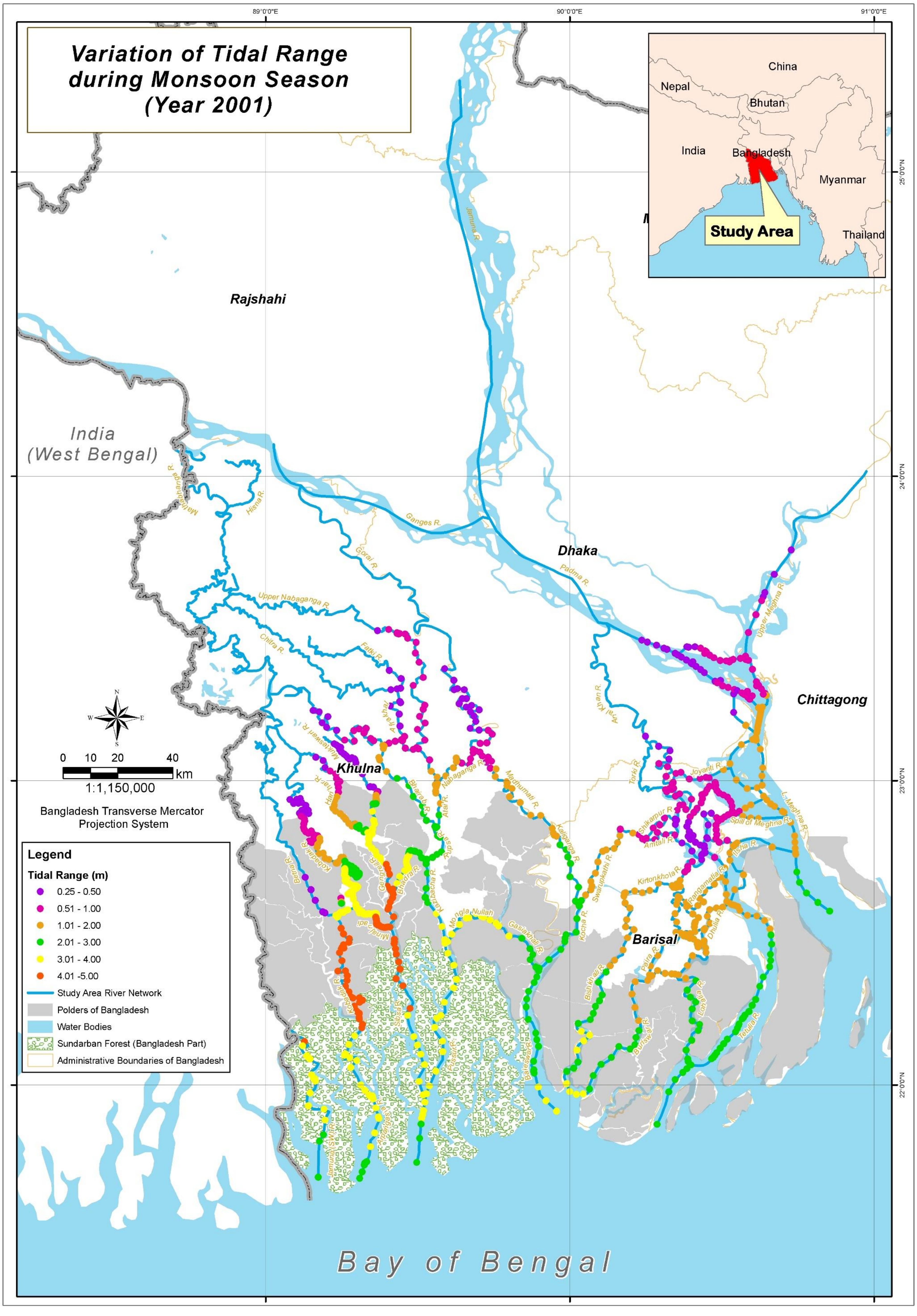


Figure 5-2: Tidal range along the rivers in the monsoon season, year 2001

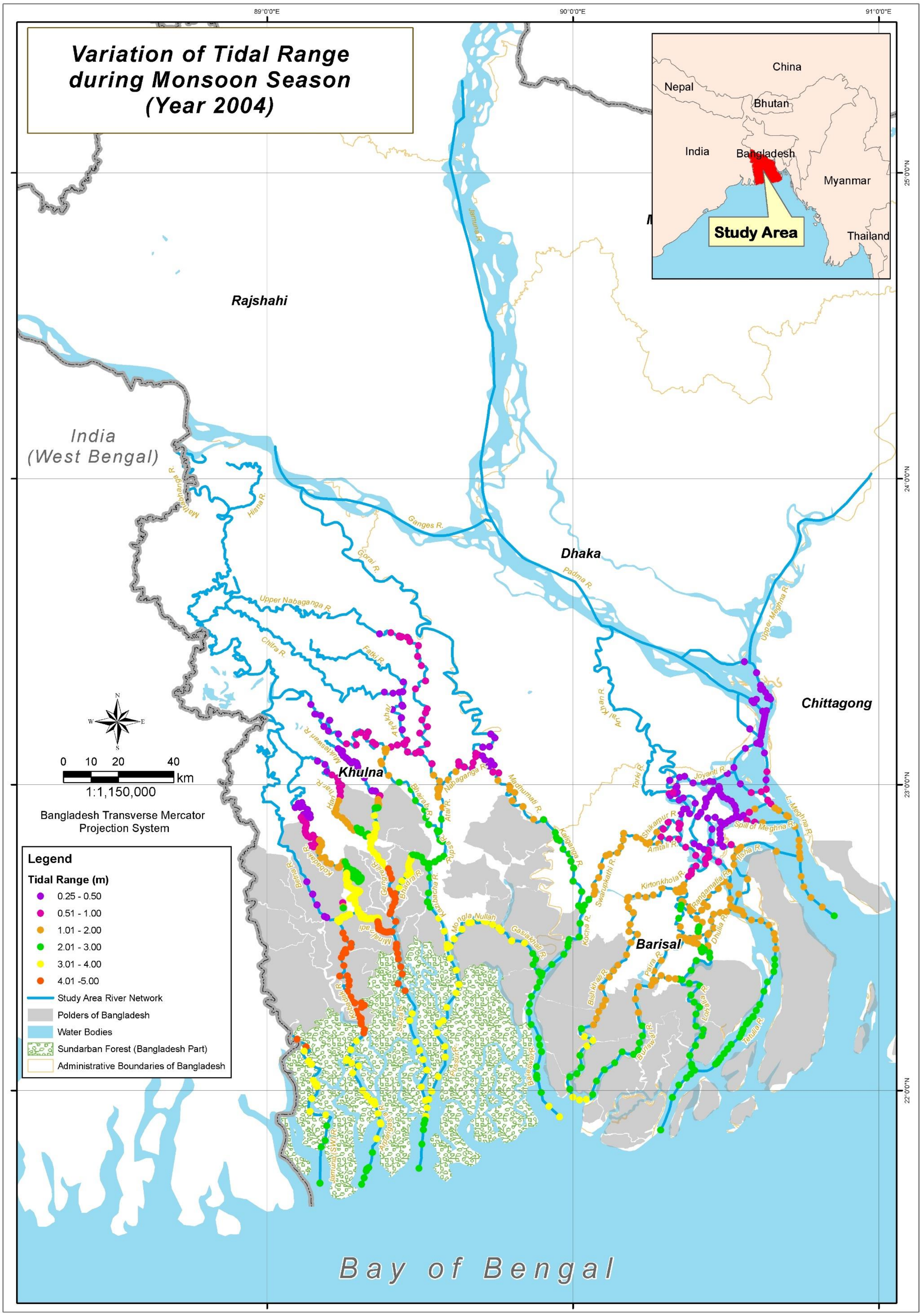


Figure 5-3: Tidal range along the rivers in the monsoon season, year 2004

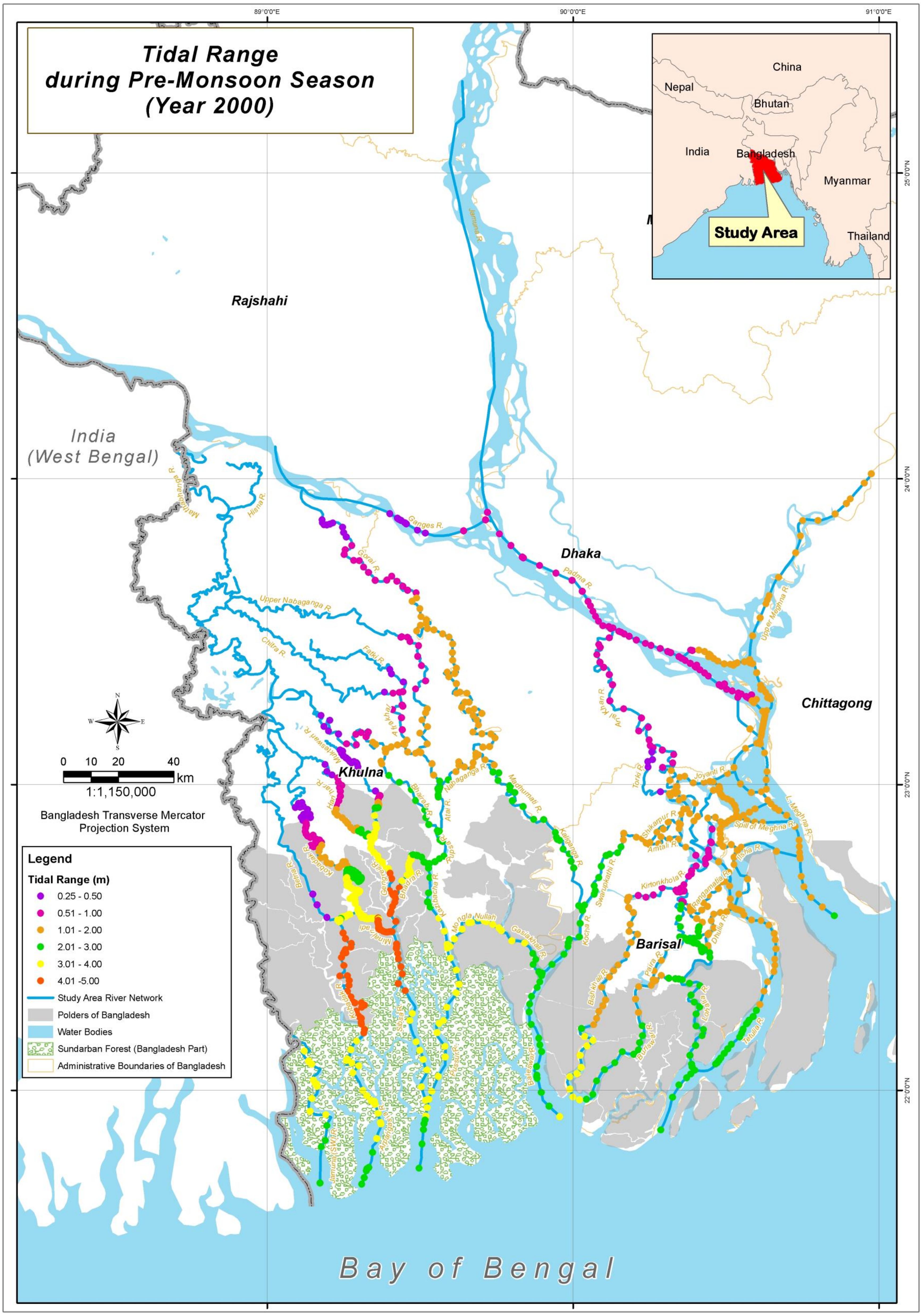


Figure 5-4: Tidal range along the rivers in the pre-monsoon season, year 2000

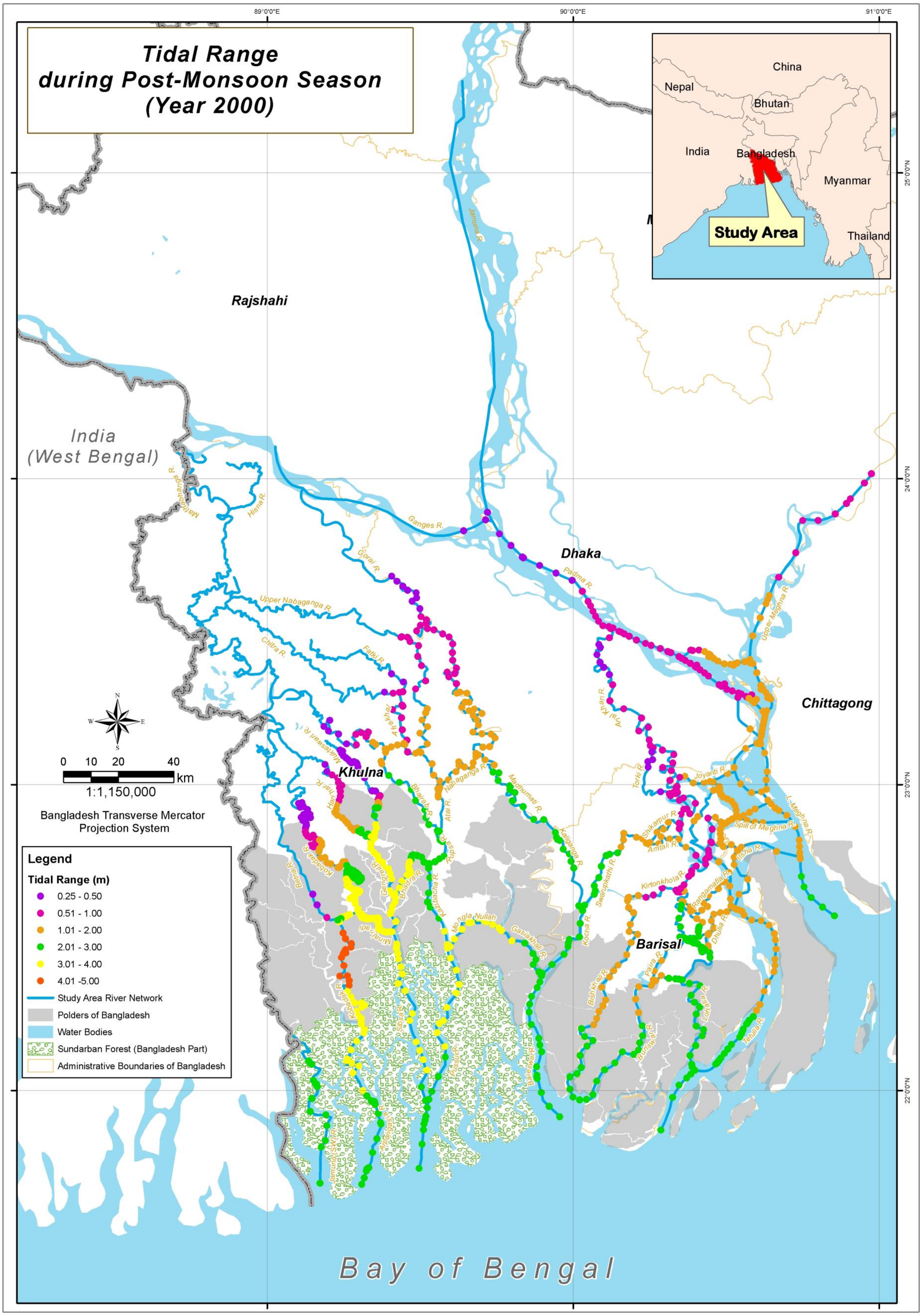


Figure 5-5: Tidal range along the rivers in the post-monsoon season, year 2000

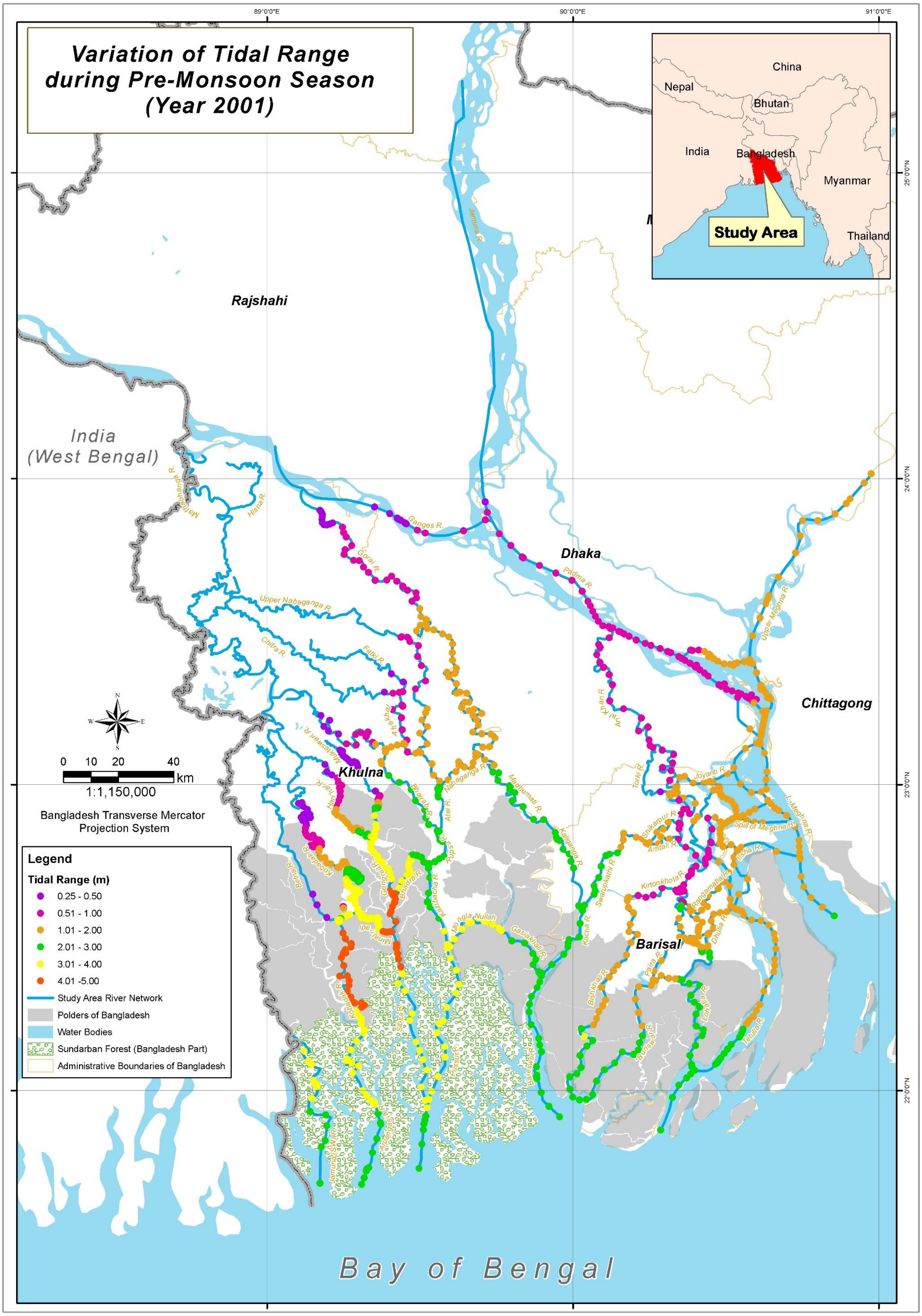


Figure 5-6: Tidal range along the rivers in the pre-monsoon season, year 2001

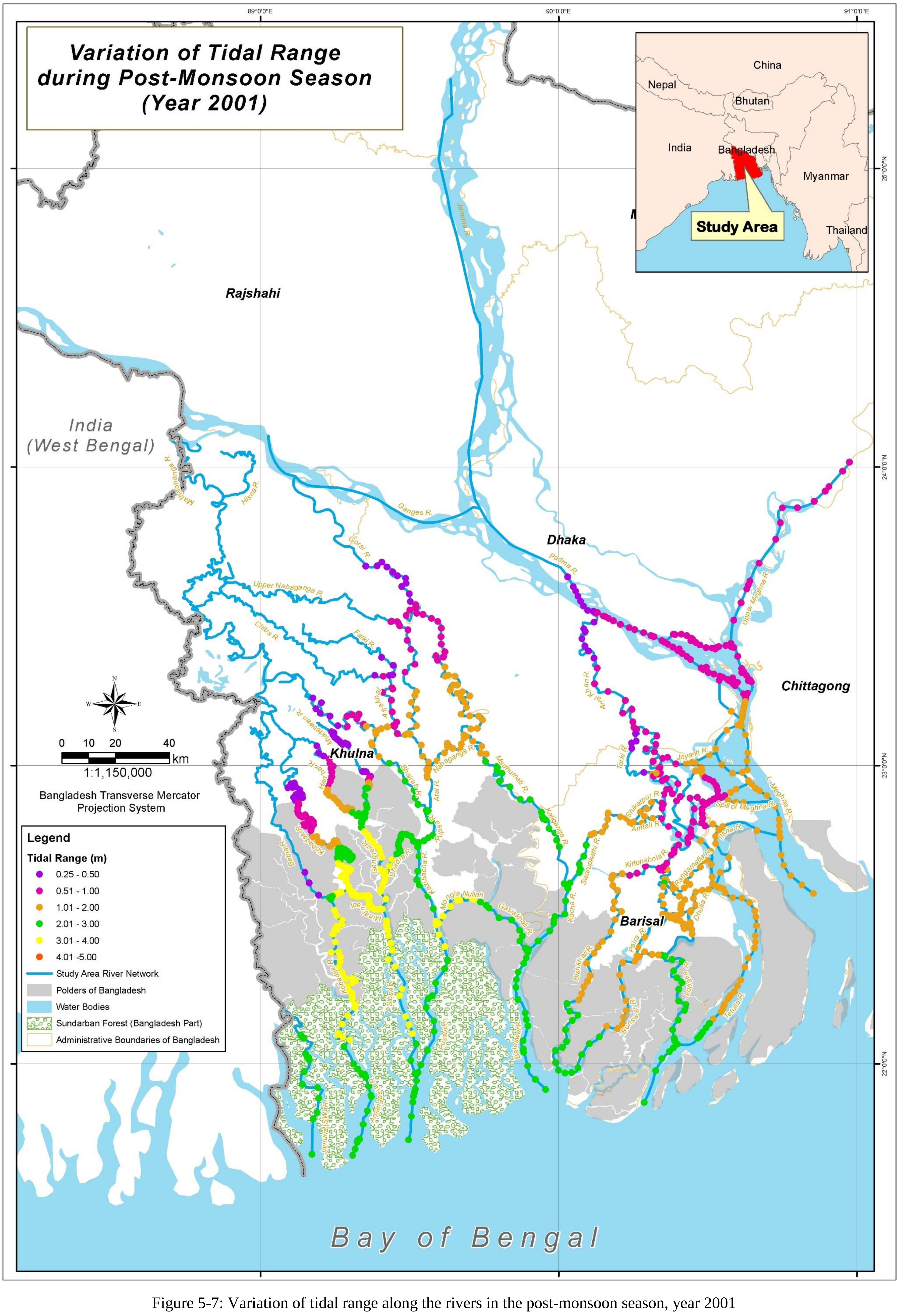


Figure 5-7: Variation of tidal range along the rivers in the post-monsoon season, year 2001

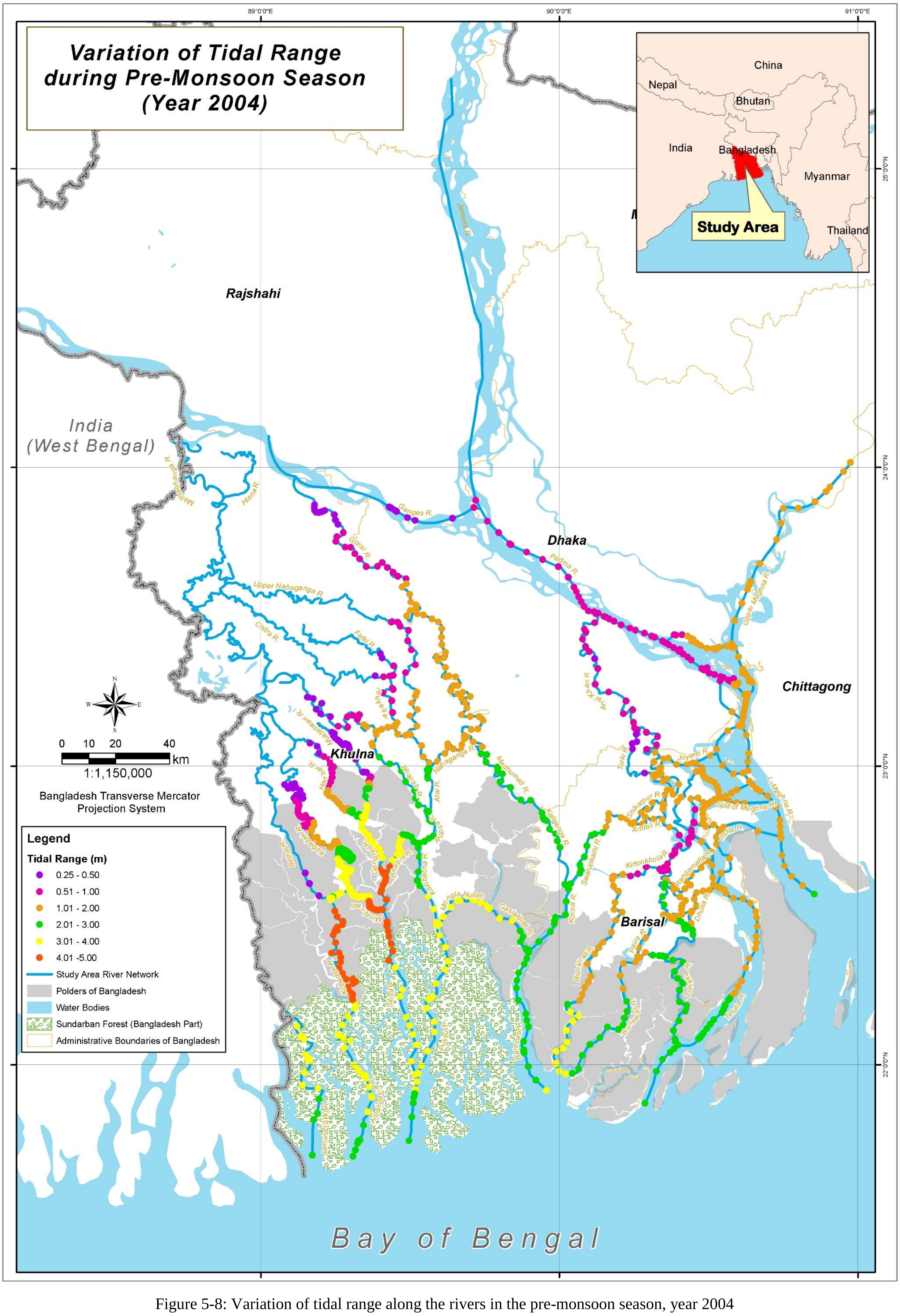


Figure 5-8: Variation of tidal range along the rivers in the pre-monsoon season, year 2004

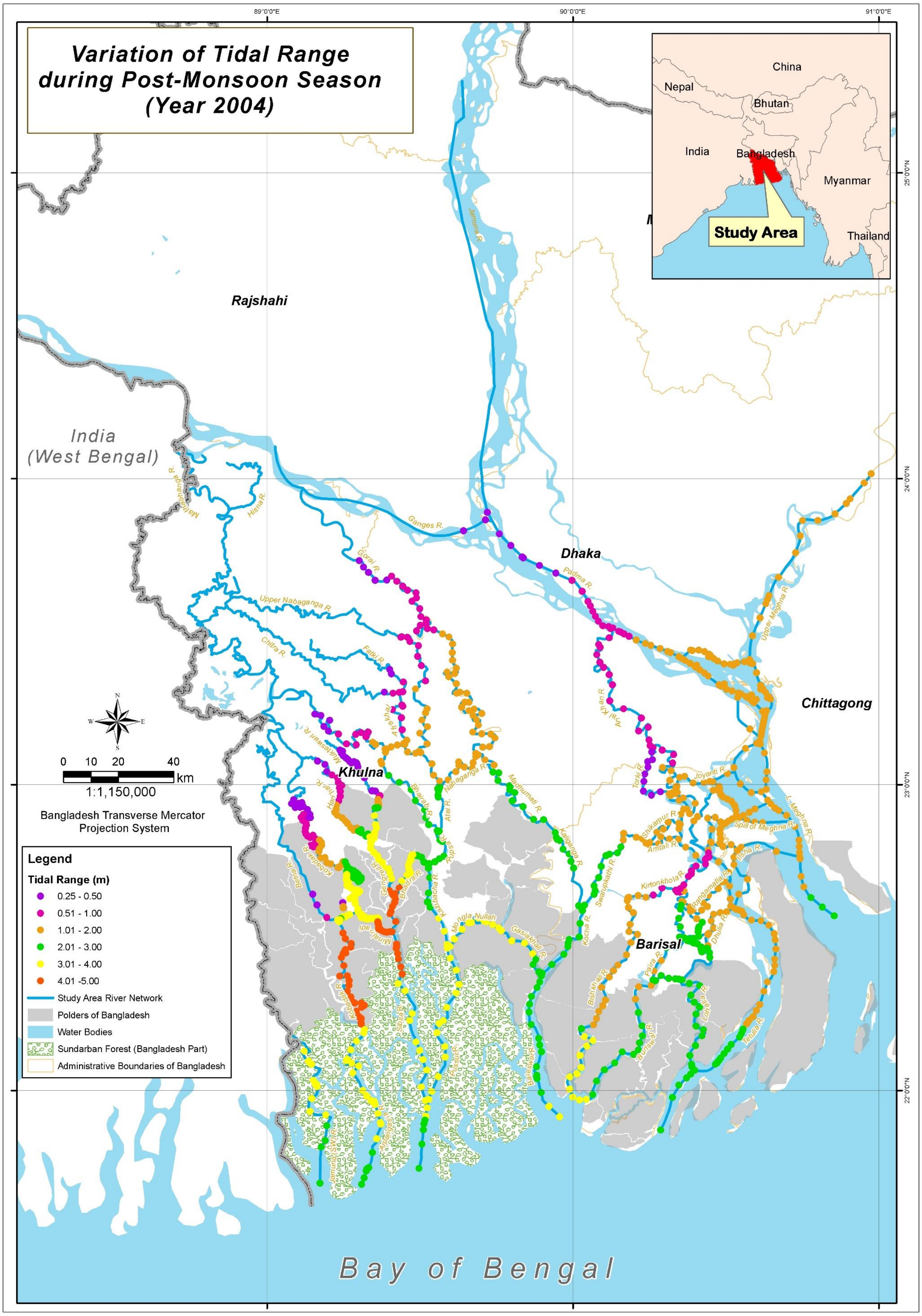


Figure 5-9: Variation of tidal range along the rivers in the post-monsoon season, year 2004

5.1 Variation of Tidal Range for The Year 2050 and 2080

The hydrodynamic model was used to simulate the conditions of climate change for years 2050 and 2080. The river discharge is increased at the upstream boundary of Ganges, Padma, Meghna (upper), and the mean sea level was increased at the rivers' mouth according to Table 2-2. The obtained tidal range for monsoon seasons for the year of 2050 and 2080 are shown in Figure 5-10 and Figure 5-11. According to our model results, no substantial changes are expected with respect to the monsoon season of the base year 2000.

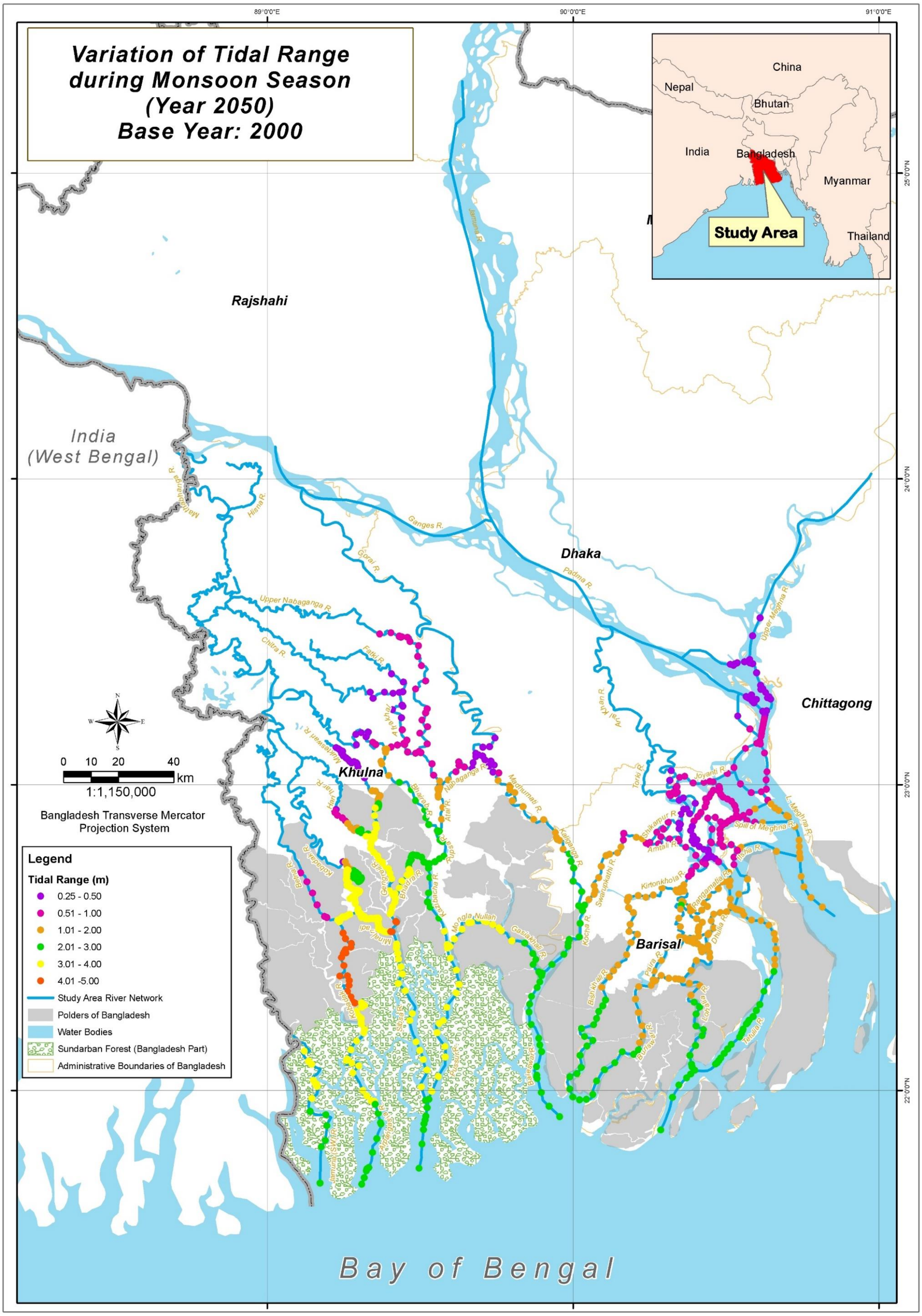


Figure 5-10: Variation of tidal range along the rivers in the monsoon season, year 2050

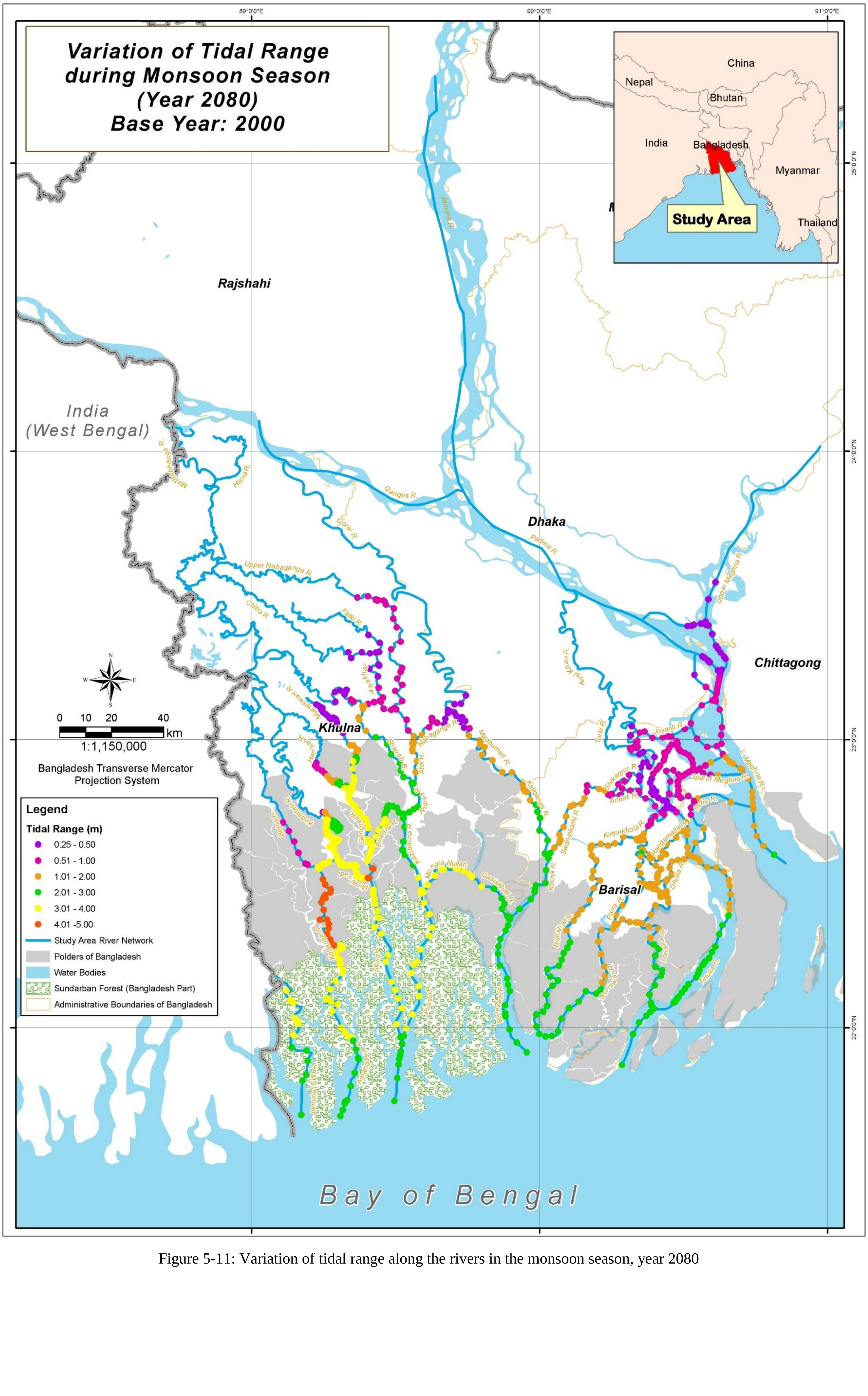


Figure 5-11: Variation of tidal range along the rivers in the monsoon season, year 2080

5.1 Spatial variation of Suspended Sediment Concentration, Sediment Load and Discharge

To understand the behavior of cohesive sediment along a particular river (Gorai-Madhumato-Kaliganga-Kocha-Baleswar river) in the study area, the comparison was made between suspended sediment concentration, sediment load and discharge for the flood tide and ebb tide. The data for the graph was taken from the cohesive sediment transport model.

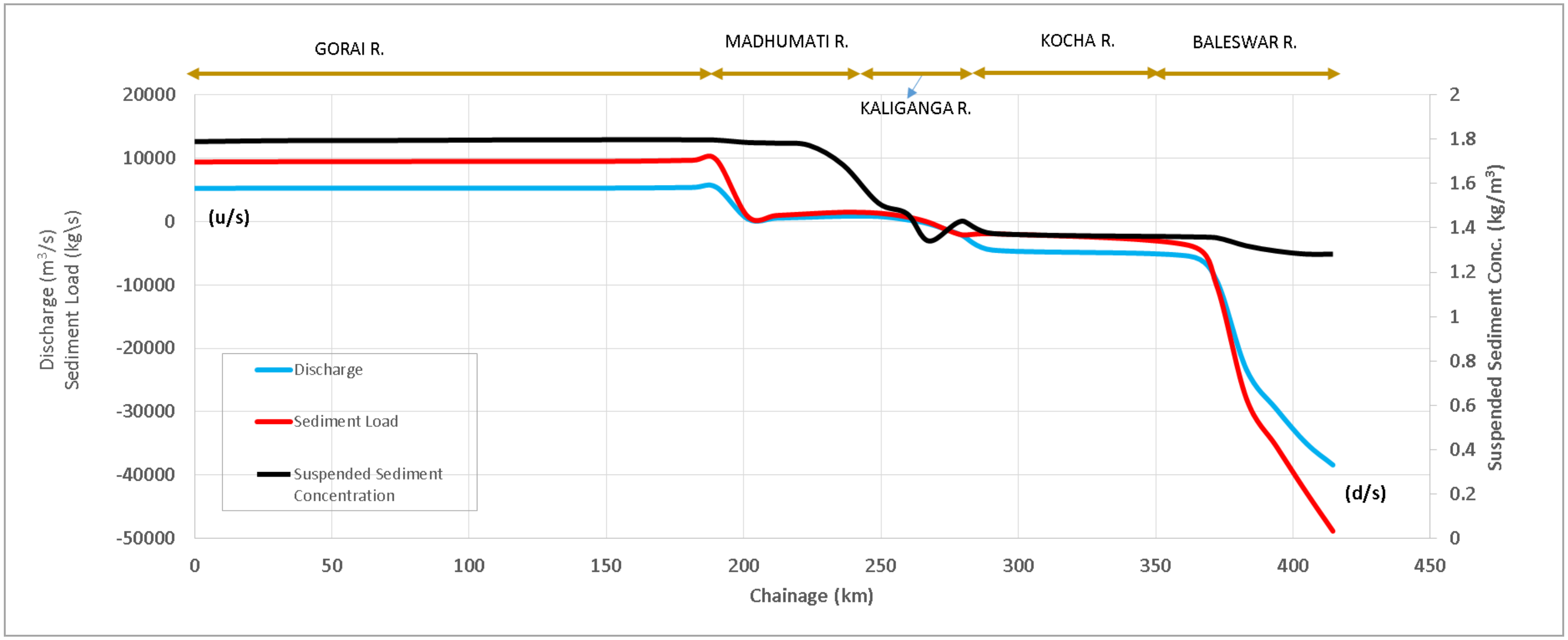


Figure 5-12: Spatial Variation of discharge, sediment load and suspended sediment concentration during the flood tide of 1st August, 2000, 9:30 AM

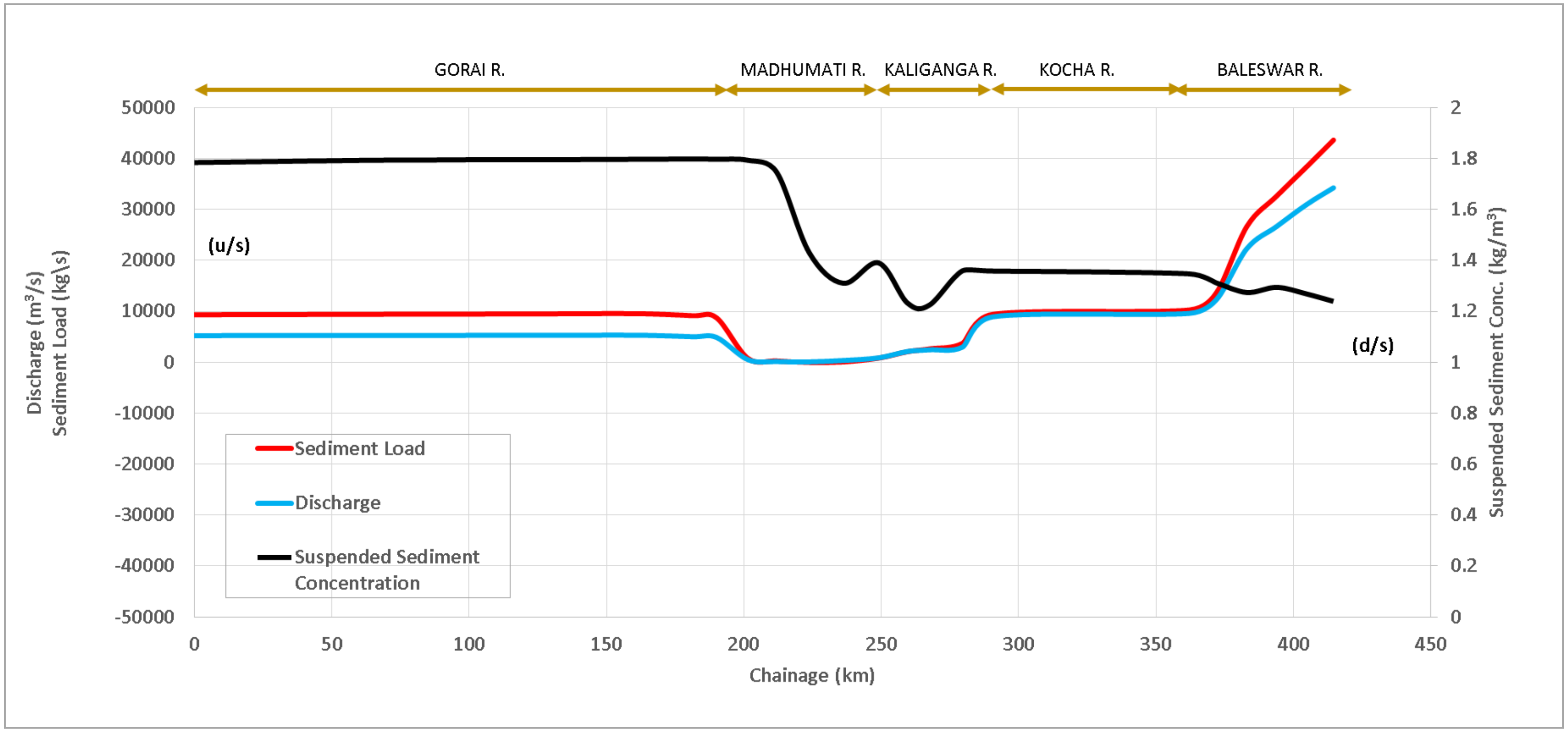


Figure 5-13: Spatial Variation of discharge, sediment load and suspended sediment concentration during the ebb tide of 1st August, 2000, 3:30 PM

CHAPTER 6: Discussions

Generally, the Tide intrudes more landward in the dry year (2001) than the base year (2000) which is true for this study. The 1 m tide advances 17 km more in the Nabaganga (lower) river in the monsoon season of 2001 than year 2000. The tidal range is around 4 m in the kobadak and sibsa river for year 2004, which is greater than year 2000.
The tidal ranges has strong seasonality. 1 m range tides intrude landward 77 km more in the gorai river in the premonsoon season of year 2000 than monsoon season of the same year.
At the western side of the study area (namely Sibsa and Kobadak river), the tidal range initially increases upstream and decreases as the tidal energy diminishes.
There is no significant change in tidal variation in for all three season between the climate change year 2050 and 2080.
The suspended sediment concentration (SSC) of the lower Meghna river governs the whole study area. For the gorai-madhumati-kaliganga-kocha-baleswar river branches, the SSC gradually decreases as it approaches the Baleswar estuary. The sediment load gradually decreases away from the coast. There is discharge reversal points in madhumati and kaliganga river because of which the velocity is low in these branches.

CHAPTER 7: Conclusions and Recommendations

Only some of the objectives were met. Consequently, the study was unable to fulfill one of the objective of investigating the movement of turbidity maxima in the south western rivers of Bangladesh due to unexpected circumstances of data unavailability.

The advection dispersion model for cohesive sediment was only simulated for suspended sediment. The salinity component and other turbidity component was not included because of data constraints.

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