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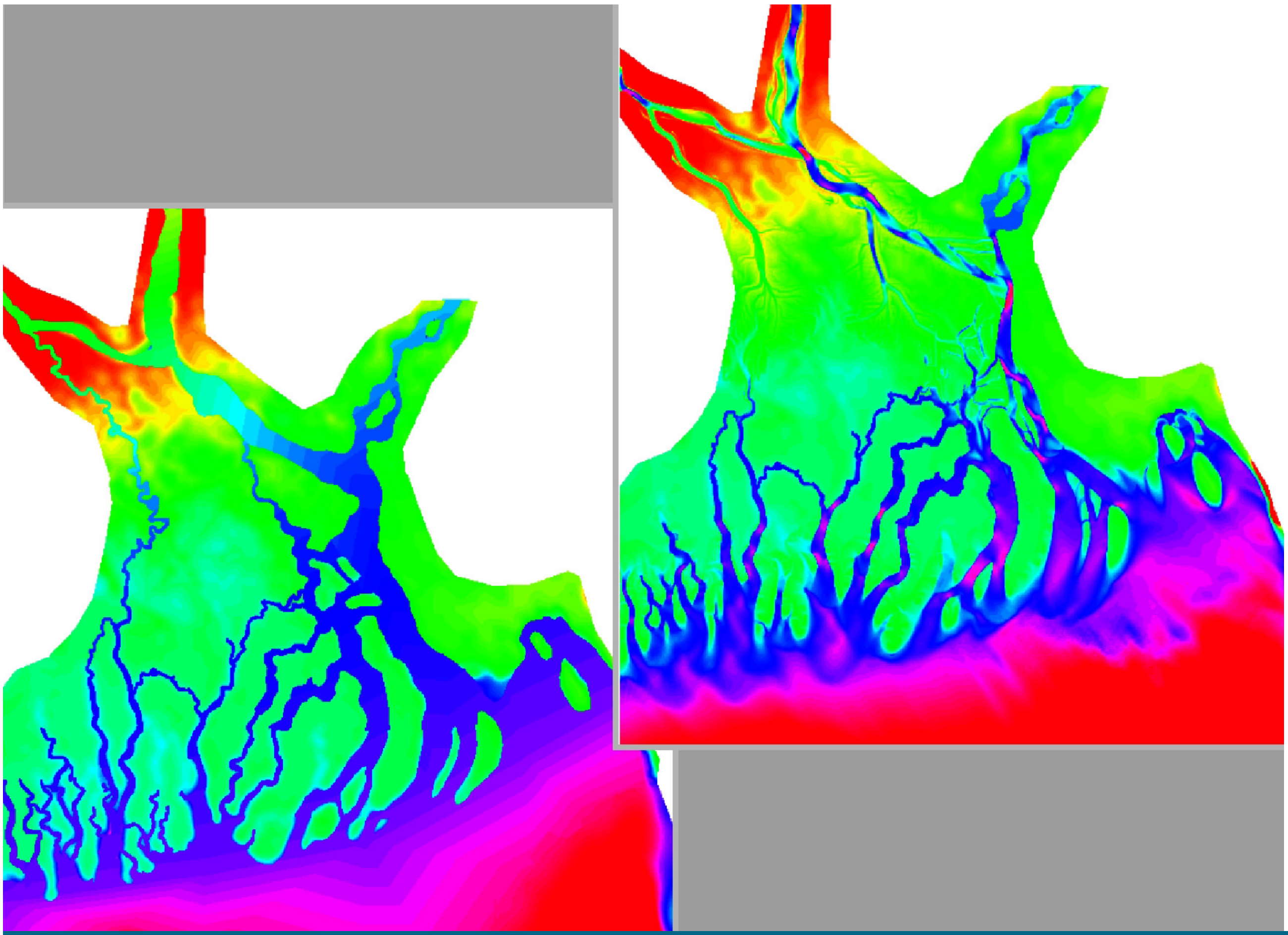

Modelling Centuries of Geo-Morphological Development of the Ganges-Brahmaputra-Meghna Delta

Jakia Akter

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DISSERTATION

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To my parents

Shamsunnahar Mukul and Md. Mohiuddin Miah

QUOTE

“If you fail, never give up because F.A.I.L. means First Attempt In Learning.
End is not the end, if fact E.N.D. means Effort Never Dies.
If you get No as an answer, remember N.O. means Next Opportunity.
So let's be positive. "

-Dr. A.P.J. Abdul Kalam

Abstract

Data about the geometry and bathymetry of rivers and estuaries is lacking in many large-scale delta systems. The Ganges-Brahmaputra-Meghna (GBM) delta is a good example of a large system with sparse data. The purpose of this project is to increase our understanding of the geomorphological evolution of the GBM delta on a decade-to-century scale in order to better understand the physical processes that generate this delta and forecast future challenges to sustainable development in delta areas.

A process response model, both numerical and conceptual, is an outcome of this research that would be able to predict the dynamic system as a response to climate change, sea-level rise, subsidence and other influences. The behaviour of the delta and estuary system has been studied at timescales ranging from days to millennia. To identify key events and drivers over the last 250 years, the history of the estuary has been reconstructed, mainly based on a literature review and available historical maps (1776 Rennel's, 1840 Tasin's, and 1943 Topo Map) and time-series satellite images. The trends of sediment supply described in the literature have been found to be decreasing in recent years. The reason is attributed to less sediment production in the catchment by natural events like landslides, better sediment management, and sediment trapping by dam/barrage construction in the upper regime. The 1950 Assam earthquake, tectonics, excessive river flow, and sediment supply have all been identified as major external influences in the formation of the delta last century.

A 1D model of the GBM delta, developed in this study, skillfully reproduces observed hydrodynamic data on a schematized bed. No equilibrium bed profile was found within 400 years of run time under unchanged boundary forcing, although morphological development became significantly slower after 200 years. Scenarios to mimic future behaviour of the delta, how aggradation of river beds as a result of rising sea levels.

A 2D process-based morphological model (Delft3D) has been developed to reproduce the bathymetric evolution over time, including the associated sediment budget. Model results show a unique, process-based sediment budget simulation for the GBM system. The 2D model started with flattened bathymetry and it was run morphodynamically to develop a realistic channel pattern. The computed tidal propagation and mean water levels were compared well with observations. The morphological pattern developed by the model was found to be similar to the observed patterns in 2005.

The 2D modelling results suggest that the average sediment transport of the Ganges and Jamuna systems varies between 200 and 1100 million ton/year and 80 and 228 million ton/year, respectively, whereas the transport in the Upper Meghna River is negligible. Sand accounts for less than 20% of the sediment load in the system on an annual basis. These findings are consistent with observations. The 2D model also exhibits about 22% of sediment deposits in the delta system on floodplains and tidal plains. Most deposition-prone sub-regions are the Padma, Gorai, Pussur-Sibsa, Bishkhali, Shahbajpur channel, Lower Meghna, Tentulia Channel, and Arial Khan rivers. The remaining 78% of the sediment causes subaquatic delta progradation and is lost in the deep ocean bed.

The 2D model has proven to be a valuable tool to understand the GBM delta at decadal to centennial time scales for planning and sustainable development. Different scenarios of climate change and human interventions may be easily adopted. The model can be improved, for example by better initial conditions of bed composition based on new measurements. Also, derived models with higher spatial and time resolution may give a better view and understanding of local morphological developments.

Samenvatting

In veel grootschalige delta systemen zijn data met betrekking tot de geometry en bathymetry van rivieren en estuaria slechts beperkt aanwezig en beschikbaar. De Ganges-Brahmaputra-Meghna (GBM) delta is een goed voorbeeld van zo'n grootschalig system. Het doel van de huidige studie is om de kennis van de geologische ontwikkeling van het GBM system over tijdschalen van decaden tot eeuwen te verbeteren en de fysische processes die de GBM Delta vormgeven beter te begrijpen teneinde de impact van toekomstige bedreigingen voor duurzame ontwikkeling beter te kunnen voorspellen.

De uitkomst van deze studie is een zowel numeriek als conceptueel process-response model dat in staat is om de reactie van de GBM delta system op klimaatverandering, zeespiegelstijging, verzakking en andere invloeden, te voorspellen. Het gedrag van het delta system is bestudeerd op tijdschalen van dagen tot millennia. Om de belangrijkste forceringen en gebeurtenissen over de laatste 250 jaar te identificeren zijn de historische ontwikkelingen gereconstrueerd op basis van literatuur onderzoek en beschikbare historische plattegronden (1776 Rennel's, 1840 Tasin's, en 1943 Topo Map) en tijdseries van sateliet beelden. De literatuur beschrijft dat sediment aanvoer een afnemende trend laat zien afgelopen jaren. Een mogelijke verklaring is dat er minder sediment los komt in het stroomgebied door natuurlijke processen zoals aardverschuivingen, beter sediment management technieken, en sediment invang door stroomopwaartse ontwikkeling van dam reservoirs. De Assam aardbeving in 1950, tectoniek, extreme rivier afvoer, en sediment toevoer zijn aangewezen als de voornaamste externe forceringen die de GBM delta afgelopen eeuw hebben vormgegeven.

Een 1D model van de GBM delta, ontwikkeld in deze studie, kan de huidige hydrodynamica voorspellen op een geschematiseerde bodem. Hoewel de morphodynamische ontwikkeling significant minder werd na 200 jaar, leidde het 1D morphodynamische model na 400 jaar niet tot een evenwichtsbodem onder constante hydraudynamische forcering. Model scenarios om toekomstig gedrag van de GBM delta te bestuderen laten een verhoging van het rivierbed zien ten gevolge van zeespiegelstijging.

Een 2D morfodynamisch model (Delft3D) is ontwikkeld om bodem veranderingen en sediment budgetten te reproduceren. De model resultaten leiden tot een uniek gemodeleerd sediment budget van de hele GBM Delta. Het 2D model start vanaf een vlakke bodem, waarna zich realistische geulpatronen ontwikkelen. De berekende getij voortplanting en gemiddelde waterstanden komen goed overeen met observaties. De gemodelleerde morfologische geul patronen zijn vergelijkbaar met de geobserveerde patronen uit 2005.

De 2D model resultaten suggereren dat het gemiddelde sediment transport van de Ganges en de Jamuna varieert tussen, respectievelijk, 200 en 1100 Mton/jaar en 80 tot 228 Mton/jaar, terwijl het sediment transport in de Upper Meghna rivier verwaarloosbaar is. Op jaarlijkse basis draagt zand minder dan 20% bij aan de sediment toevoer, terwijl het overige deel bestaat uit fijner material in suspensie. Deze model resultaten zijn consistent met observaties. Het 2D model laat ook zien dat ongeveer 22% van de sediment toevoer neerslaat in uiterwaarden in de delta met name in de Padma, Gorai, Pussur-Sibsa, Bishkhali, Shahbajpur channel, Lower Meghna, Tentulia Channel, and Arial Khan rivieren. De overige 78% van het sediment draagt bij aan de uitbouw van de subaquatische delta of verdwijnt in de diepere ocean.

Het 2D model is een waardevol instrument om de GBM delta op macro-schaal beter te begrijpen op tijdschalen van decaden tot eeuwen ten behoeve van planning en duurzame ontwikkeling. Daarbij kunnen verschillende scenarios van klimaatverandering en menselijk ingrijpen makkelijk toegepast worden. Het model kan verbeterd worden, bijvoorbeeld door betere beginvoorwaarden te definieren voor de bodem samenstelling op basis van nieuwe metingen. Ook kunnen afgeleide modellen met hogere resolutie in tijd en ruimte een meer gedetaileerd beeld geven van locale morfologische ontwikkelingen.

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Chapter 1
Introduction

This chapter briefly introduces the research background, defining a tide-dominated delta, and introduces the Ganges-Brahmaputra-Meghna delta system, problem description of the area, and its millennium-scale delta evolution and century-scale delta development. Then research problems are described and research objectives and related research questions are formulated. A brief description is provided of the research approach and expectations from this research. Finally, chapter-wise an outline of this thesis is made.

1.1 Research Background

1.1.1 Introduction

Deltas are the habitat of more than half a billion of the world’s population (Syvitski *et al.* 2009), due to their direct and indirect ecosystem services. Though the coastal areas are highly vulnerable to extreme events, such as storms with substantial societal and economic costs (Nicholes and Fisher, 2007) and global sea-level rise (SLR), population densities in the coastal region is more than three times higher than the global average (Small and Nicholes, 2003). Coastal erosion is a very common phenomenon due to sediment deficiency caused mainly by human interventions, such as the construction of a large number of dams, water diversion structures, and improved sediment management upstream. In contrast, the Bengal delta is rich in fluvial sediment input till now, due to less intervention in the river's catchment and intensive upstream agriculture practice.

The Bengal delta, mostly covering Bangladesh, has been recognized as the biggest delta on the planet (Gupta, 2007; Akter et al, 2016). It drains almost all of the Himalayas, the most sediment-producing mountains in the world, through the three main river systems: the Ganges, Brahmaputra, and Meghna (GBM), as shown in Figure 1.1. These systems are characterized as the world's largest sediment load conveying systems. More than one billion tons of sediment each year, of which about 80 percent is conveyed during the four monsoon months, is transported through the GBM system (Goodbred and Kuehl, 2000b). As a result, the delta has been prograding at a high rate. Bangladesh, with more than two percent of the world’s population and a density of more than 1080 people/sqkm (Steckler et al., 2010), has a highly vulnerable coastal environment (Minar, Hossain, and Shamsuddin, 2013).

SLR of one meter (1 m) would cause immersion of 17% to 21% of the aggregate region of Bangladesh (Choudhury, Haque, and Quadir, 1997; IPCC, 2001). Since the greater part of the zone is under five meters above the mean ocean level, as per the advanced rise demonstrated, it could be vulnerable to higher SLR and a high rate of subsidence. Contrasts in assessments are found in the literature on the effects of environmental change and subsidence. To address these effects in the coming decades, it is important to survey the current thinking on the future of the delta. Many studies have been completed on floodplain inundation in this tide-dominated delta. However, most delta models consider a static (i.e. bathymetry fixed in time) waterway framework when they evaluate the long-term impacts of environmental change.

Deltas in general are vulnerable to climate change and global SLR and it is suspected that the Bengal delta would be amongst the worst victims of climate change (Ahmed, 2006). Therefore, a long-term integrated plan for sustainable development is needed to make a safe and inhabitable delta in the coming centuries. One of the important requirements for efficient and effective planning is a sound knowledge of the long-term physical processes in the GBM delta.

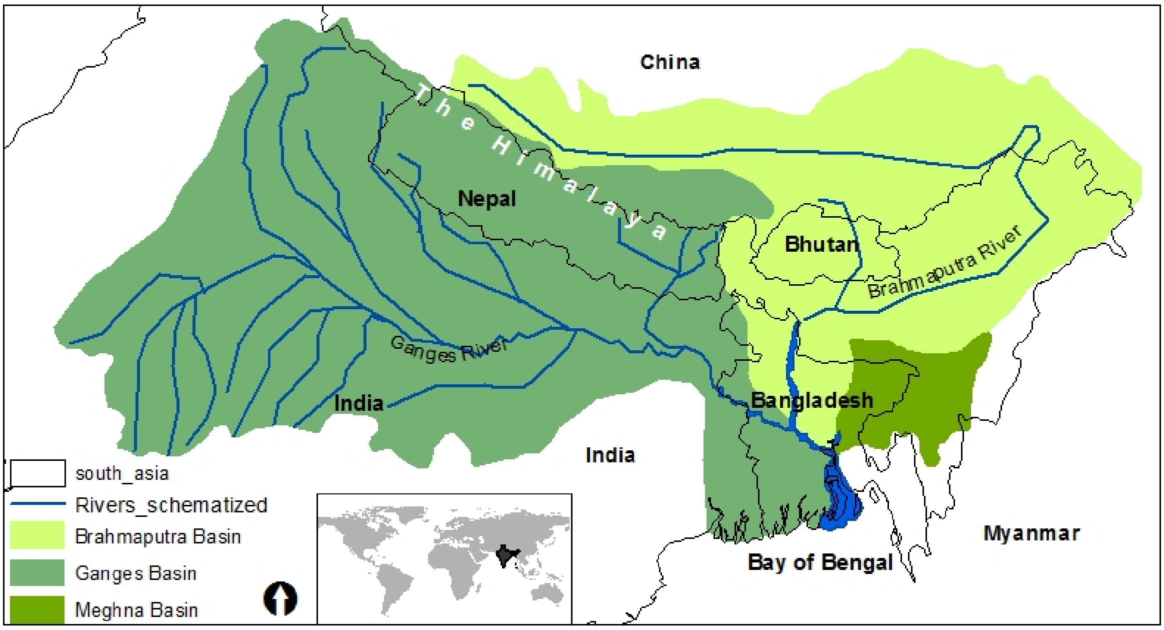


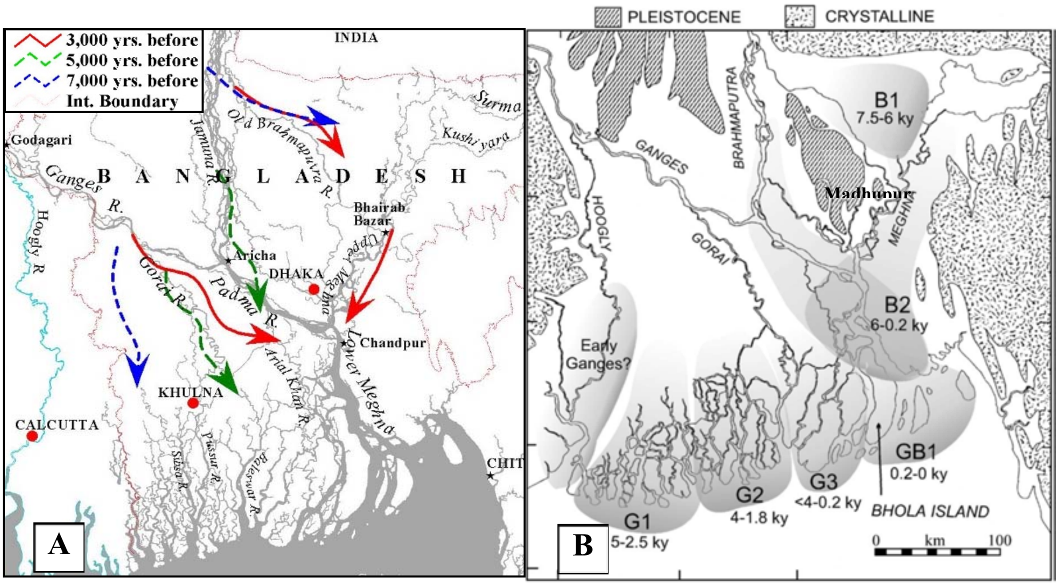
Figure 1.1: Physical setting of Bangladesh and three basins

1.1.2 Ganges-Brahmaputra-Meghna delta

The Bengal delta is an active tide-dominated delta, where tides play an important role in the sediment dispersal process. The Himalayas, the source of the Ganges and Brahmaputra rivers, have a large sediment production in their basins caused by heavy rainfall driven by monsoon climate and high relief produced by active crustal movements (Saito, 2001, as reported in Hori and Saito, 2007; Colman, 1969). Hence, the Ganges-Brahmaputra River is one of the three largest riverine sources of water and sediment for the world's oceans; 1.06 billion tons/year (Hori and Saito, 2007). This makes the system morphologically very active. Compared to other large rivers, both the Ganges and Brahmaputra rivers have experienced relatively little human interference until recently. Due to high population density and intensive agricultural practices, these river catchments produce huge sediment that is carried by the Ganges and Brahmaputra rivers, which results in the continuous progradation of the delta (Sarker et al, 2003). This process has contributed to the present size of the delta which is about 100,000 sqkm (Sarker et al 2013). Most of the large deltas are suffering from sediment starvation and coastal erosion due to human interventions, such as the construction of large dams, water diversion structures, and improved sediment management upstream. In contrast, the Bengal delta has been prograding very rapidly at a rate of 17 sqkm/year during the last five decades (Sarker et al, 2011), although the rate has been reduced to 7 sqkm/year during 2008-2020 (Sarker, et al., 2021). Delta progradation always makes the river system unstable and dynamic causing the delta to become a very dynamic system with rapid changes.

1.1.3 Millennium Scale Delta Evolution

Much research on this delta has been carried out on the millennium time scale. Among those, Umitsu (1993), Goodbred and Kuehl (2000a, & b), and Allison and Kepple (2001) have shown the phases of delta evolution and delta progradation in the Holocene period. Based on the compiled borehole data, Goodbred and Kuehl (2000a) developed palaeo-geographic maps of the Ganges and Brahmaputra delta (Bengal delta) during the Holocene (approximately last 11,650 years). The palaeo-geographic maps show the shifting of the Ganges River from west to east while avulsion of the Brahmaputra River occurred several times between the east and west sides of the Madhupur Tract (Goodbred and Kuehl, 2000a). Figure 1.2 shows the Millennium-scale delta development in phases. They concluded that changes to the courses of the Ganges and the Brahmaputra rivers were a consequence of the delta building process, which was itself driven by abundant sediment input from erosion of the Himalayas, conditioned by the sustained SLR that began during the Late Quaternary (refers to the past 0.5–1.0 million years) and modified internally by regional tectonics within the Bengal basin.



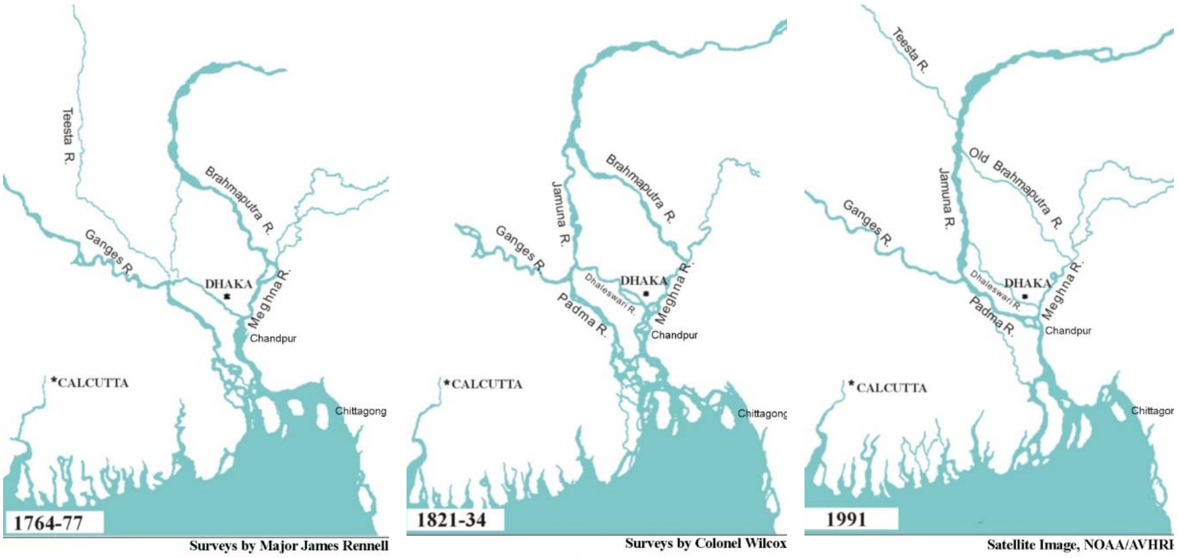
source: Allison et al (2001)

Figure 1.2: Map of (A) Palaeo-geographic map [based on: Goodbred and Kuehl (2000a)], and (B) the pathways and timing of the phases of late Holocene growth of the lower delta plain associated with the Ganges (G1, G2, G3), Brahmaputra (B1, B2), and combined Ganges–Brahmaputra (GB1).

1.1.4 Century Scale Delta Development

Apart from thousand to millennium scale studies on the delta, very sparse studies have been carried out on a decade to century-scale (10 to 100 years) in modern times. Sarker et al (2013) have indicated the century-to-decade scale delta development process. They mentioned that the Bengal delta is mainly prograding along the Meghna Estuary. During the last 250 years, the location of the delta building estuary shifted eastward and later westward, as shown in Figure 1.3. In the same period the distributaries, which also contributed to the delta building processes, shifted their courses to the southwest direction, the dominating direction of which was mainly southeast about 200 years ago. For such a case of river shifting, land and river morphology should not be considered as ‘fixed’, which could be misleading for sustainable future development in this delta.

The Meghna, which is the active delta of the GBM basin, is located on a somewhat shallow and wide shelf, which falls past its southern tip into a lower basin (Ali et al. 2007). The shape of this estuary resembles an inverted funnel that runs south across the larger section of the shelf. Some of the enormous sedimentary load carried by the GBM rivers, in particular Bhola (an administrative district), Hatiya (an administrative upazila), and Monpura (an administrative upazila) along with other islands, have helped to create some of the largest alluvial islands of the estuary. Erosion, along with new land development around all of these islands are very usual. There are countless subaqueous islands in our estuary system. Only along the Chittagong belt, i.e. mostly beyond the Meghna estuary, are prominent marine activities, notably northward long coastline movement of sediments (Barua, 1991). On the other hand, the west side of the estuary is dominated by fluvial processes.



source: ISPAN, 1995

Figure 1.3: Development of the main rivers in Bangladesh over time

The characteristics of different parts of the delta are different based on their active processes. The western part of the Bengal delta (southwest region of Bangladesh) is a moribund delta where the delta building process is inactive; henceforward tidal asymmetry is present here for riverbed sedimentation during the tidal slack time (Sarker, et. al., 2021). The tidal process governs this region and thus the estuary systems in the western part of the delta are tide-dominated. On the other hand, the eastern part of this delta, a combination of the Meghna Estuary and its three main Channels (Tentulia, Shahbajpur, and Hatiya), is an active delta where the fluvial process prevails. And in between these two types of the delta, the boundary of the transition zone is not identified yet. Although the formation of delta processes may be identical, the functionalities of these two types of the delta are quite different. The changes in the physical processes in the coming decades could be more rapid which would have long-term implications in the planning process. So, the modalities of any long-term planning in these areas should need to be distinctive.

1.1.5 Natural and Anthropogenic Drivers

Many natural and anthropogenic drivers prevail here, for shaping and forming this delta. Among the natural drivers, exogenous causes are not generated from the basin such as seismic events; while endogenous causes are produced within the river basin such as flooding. It is believed that an earthquake in the late-18th century caused the Brahmaputra River to divert its flow from its earlier course of the Old Brahmaputra River to the present course of the Jamuna River, keeping the Madhupur Tracks on the east. This single change invited several other series of geo-morphological changes in the delta with long-term implications on the delta development process. There are indications of river avulsion in the northeast region of Bangladesh during the high flood season. On the other hand, among the anthropogenic interventions, the implementation of the Farakka Barrage in India during the 1970s resulted in a drastic reduction of the dry seasonal flow of the Ganges River, which has caused a reduction of fresh water flow to the southwest region of Bangladesh. As a consequence, salinity in the southwest region has increased considerably with pronounced effects on agricultural lands, fisheries, the Sunderbans mangrove ecosystem, and thereby on the lives and livelihoods of the coastal people.

There are some zones in the delta where subsidence is noticeable. Some researchers have indicated that this delta is sinking at a rate of 8-18 mm/year (Syviski et al, 2009), although the rate of subsidence was found to be different by a study carried out by Sarker et al (2012). Nevertheless, any small rate of subsidence in this delta has prolonged consequences in terms of changes in landforms and river shifting. Conversely, SLR, another key driver in the delta area, would also have a few other responses to the physical processes in the delta area. Adapting to global climate change, Nicholls *et al.* (2007) pointed out that the insight into processes at decade to century-scale is required; whereas and Donnelly et al. (2004) mentioned that the understanding of this decade to century-scale process is least developed.

1.1.6 Process-based Approach

The slope of the riverbed, the depth of the water at the mouth of the river, and the mean sea level (MSL) are significant factors for the understanding of the system's long-term behaviour. Modelling efforts would help to understand this behaviour and the impact of future scenarios including the impact of SLR. However, the required bathymetric data are local and scarce. There is no bathymetric data describing the entire system, let alone sequences of bathymetric development to validate a morphodynamic model. Still, numerical models with proven value by validated case studies may help to explore the long-term morphodynamic evolution of this ebb-dominated estuary.

Numerical models help to create a unique virtual laboratory system with simple or multiple complex processes. Edmonds and Slingerland (2010) have used a numerical flow and transport model, Delft3D, to find the role of sediment cohesion, i.e. sediment size and type of vegetation, in shaping the morphodynamics of deltas. Gelfenbaum et. al., (2009) used a process-based morphodynamic model for predicting sediment transport pathways and delta morphological response to changes in sediment supply in the Elwha River in Washington State, USA, because of the expulsion of two dams. Nardin and Fagherazzi (2012) explored the effects of waves on mouth bar growth with Delft3D. Elmilady et al. (2019) worked on some real data modelling in San Pablo Bay, California, the USA with Delft3D. They assessed the value of process-based morphodynamic modelling by hind-casting and forecasting 250 years of morphodynamic development. Model outcomes were evaluated against measured bathymetric developments, and the model could predict decadal morphodynamic developments in San Pablo Bay with significant skill. Guo, L. (2014) explored the fundamental effects of tidal asymmetries, river discharge, and river-tide interaction in governing residual sediment transport and associated long-term estuarine morphodynamics under the combined river and tidal forcing, based on schematized modelling mimicking the Yangtze estuary (China PR).

1.2 Defining the research

1.2.1 Research Problem

Presently the delta is being represented in some modelling works keeping the physical systems static, where a few changes are allowed to be incorporated for future prediction including climate change scenarios. However, for the decade to century-scale long-term planning, nothing can be considered as ‘fixed’ in any very dynamic delta to make it sustainable. Key drivers prevailing in this delta with their changing behaviour need to be well-addressed for representing the present active delta for any sort of future prediction.

Enhanced knowledge of the century to decade-scale development processes of the Bengal delta and its response to future changes have become essential for predicting future threats for sustainable development in the delta areas. A sound knowledge, thus, is required to understand the development processes of the geo-morphology of this delta for developing a realistic model with dynamic physical settings. A process response model will be an outcome of this research that would represent the behaviour of the dynamic system. It would also help to assess the effects of climate change, SLR, subsidence, delta shifting, and so on. Based on the research findings, indicative prediction of a century to decade scale delta development would be possible, thereby helping to make the delta plan sustainable for a longer period. Thus to develop scenarios for long-term planning assessing the century-scale development of the delta under different stresses is a crucial issue. However, knowledge of the century-scale development of the delta is limited. Enhanced knowledge of the century to decade-scale development processes of the Bengal delta and its response to the different exogenous and endigenous factors have become essential for improving the lives and livelihoods of the people, as well as for facing the threat of climate change and SLR in the coming decades.

The morphological processes in the study area are not static; rather they change temporarily and spatially in a dramatic manner. Even a single alteration in the system would cause many other changes within the system. The changes in physical processes could be unexpectedly more rapid which would have some definite long-term implications in the planning process. So, the modalities of any long-term planning in these areas should need to be distinctive. Presently the delta is being represented in many studies considering the physical processes static, which is not realistic. The Bangladesh delta is very active and the key drivers of this delta need to be well addressed for representing the active functions for future prediction. All-natural and anthropogenic drivers, as identified, are needed to be well incorporated in a single system which can be represented by a numerical and conceptual model. Even, changes in one process have a long-term implication on other changes depending on its relations with other processes. Some processes may react immediately; some may take several hundreds of years. So, a process response conceptual model could help to simulate single or multiple responses in a short period of physical processes in the delta, and this is the focus of this study; although at this stage it is uncertain to what extent it can capture the full complexity of the system. Tectonic activity and their responses will not be covered in this study, but subsidence will be considered.

From reviewing the available literature, the following research gaps were identified:

- There is much research, which addresses the Holocene development of the Bengal delta, but no study or research addresses the decade to century-scale development of the delta. Lack of data and their unreliability restrict scientists to work on this issue. But latest numerical models may help to hind-cast the delta after calibrating the results with available historical maps. This hind-cast model may be used to forecast the delta development in a short-term duration.

- Knowledge on the vertical adjustment processes of the tidal plain with the rising of RSLR/ tide level is not available, which is an important issue to fix the strategy for long-term planning to adapt to climate change-induced sea-level rise. Elevation of the tidal plain depends on the tide level and also the availability of sediment. The impact of tidal amplification for empoldering the tidal plain may also be discovered to know the impact of those human interventions. Socio-economic impacts of the intervention on the delta have been addressed by many studies. In addition, some modelling works on the poldered area have been done by IWM and CEGIS under Coastal Embankment Improvement Project Phase-1 and Phase-2 respectively. Geo-morphological impact of the tidal plain and rivers can be explored for scientific explanation.
- Another indicative study on the morphological time-scale of the main rivers, estuaries, and tidal plains to adjust with the SLR and increased flood discharge is addressed by CEGIS (2010). For long-term planning in the delta region, those time scales are important and largely depend on the availability of sediment in the context of climate change and human interventions.
- Deltaic subsidence is very much relevant for long-term planning, although recent studies indicate very high uncertain ranges from 1 mm to 25 mm per year. Further research on subsidence may provide a better estimate. An accurate rate of subsidence is needed for planning and design purposes for addressing climate change-induced SLR. A huge cost is involved with every single unit design height of the coastal structural defense.
- Coastal poldering has altered the natural land sedimentation process. If there is no sedimentation, then the land erosion phase will prevail, which is also needed along with the subsidence rate. The rate of floodplain sedimentation with the changes of SLR or tidal range and also the availability of sediment has not been studied yet, which may help for fixing the adaptation strategy against climate change and subsidence.
- The main rivers of Bangladesh have been transporting about one billion tons of sediment every year, out of which one-fourth is fine sand, and the rest of the sediment consists of silt and clay. The role of fine and coastal sediment in the land accretion process would be different. Knowledge on the role of these fine (silt + clay) and coarse (fine sand) on the lateral and vertical accretion process requires further elaborations for this delta plain.

- The development of a model on the delta development processes which can help to predict the response of the delta in the changed condition is the prime requirement for long-term planning. Prevailing processes that are already identified could be incorporated in that process response model for playing with future scenarios.

1.2.2 Research Objectives

The goal of this research is to enhance knowledge on the decade to century-scale geo-morphological development of the GBM delta to better understand the physical processes forming this delta. It is essential for predicting future threats for sustainable development in the delta areas. A sound knowledge, thus, is required to understand the development processes of the geo-morphology of this delta for developing a realistic model with dynamic physical settings. A process response model, both numerical and conceptual, will be an outcome of this research which would predict the dynamic system as a response to climate change, SLR, subsidence, delta shifting, and so on. Based on the research findings, prediction of a century to decade scale delta development would be possible, thereby helping to make the delta plan sustainable for a longer period. Thus to develop scenarios for long-term planning, assessing the century to decade scale development of the delta under different stresses would be helpful for any development planning in this area.

The specific research objectives are to:

1. Identify the prevailing morphodynamic processes, on a decade to century-scale, in the Ganges-Brahmaputra-Meghna system.
2. Identify climate change-related global and regional projections relevant for the GBM delta.
3. Describe the morphodynamic system of the data-scarce GBM delta.

1.2.3 Research Questions

Research questions are related to the time scale of the morphodynamic evolution of the system, the possible existence of (dynamic) equilibrium, the impact of river supply pulses, sediment budget, and its pathways. The following research questions are formulated to achieve the objectives of the research:

1. What are the prevailing processes, on a decadal to century time-scale, in the Ganges-Brahmaputra-Meghna system in forming the tide-dominated delta?

2. What are the climate change-related global and regional projections?
3. How can a process-based, 1-D model describe the Ganges-Brahmaputra-Meghna delta morphodynamic evolution?
4. How can a process-based, 2-D model describe the Ganges-Brahmaputra-Meghna delta morphodynamic evolution?
5. Would the application of the 2D model be robust enough to assess current date morphodynamic evolution and sediment budget?

1.3 Research Approach

In the first part of this thesis, a list of literature was reviewed for setting the knowledge scenario on this GBM delta, finding the research scope, and confirming a research method for achieving the research goals. As a result, a clear understanding of the prevailing processes or key drivers was identified along with their responses to the delta system.

Based on the selected research approach, a one-dimensional (1-D) model is adopted for simplifying the delta system. This 1-D model has proven the advantage of simplicity and implies a smaller computational time in comparison to two-dimensional (2-D) or three-dimensional (3-D) models. A 1-D model may serve to explore the morphological evolution of a river and delta system in a simplified manner. In this analysis, the GBM rivers and estuary system is schematized as a rectangular cross-section channel river with fixed banks, expanding estuary system, and an expanding long sea area. This simplifying 1-D schematization is unable to handle the interaction of flow with floodplain and coastal plain. This 1-D model defines the system parameters, like sloping bottom profile, seasonal sea-level variation, and its effect, river depth at the mouth, bed roughness, changing mean sea level, after a series of simulations. This model computes the occurrence of a tentative morphodynamic equilibrium and decade to century-scale bed level changes with and without SLR and subsidence.

Then, a process-based 2-D morphological model, Delft3D, has been used to reproduce the bathymetric evolution over time and the associated sediment budget. This 2-D model was set mimicking the geometry of the GBM system and covering some parts of the Bay of Bengal. The DEM from the National Water Resources Database (NWRD), based on the 1950s agricultural maps of the Bangladesh Water Development Board (BWDB), was used for land elevations, but detailed channel geometries were smoothed out in order to let the model freely generate realistic channel patterns. For seabed bathymetry, data generated from the Navy Charts of 2010 was used. We assessed model performance in terms of water levels and morphological patterns. These steps will demonstrate the possibilities for the application of a robust modelling system to assess the morphodynamic evolution and sediment budget and pathways. This particular delta model is expected to offer many opportunities to compare with sediment data, where it would deal with a poorly surveyed area.

1.4. Outline of the Thesis

The thesis can broadly be divided into three parts: Introduction and Overview (Chapters 1 and 2); Research results (Chapters 3, 4, 5, and 6); and Discussions and Conclusions (Chapter 7).

Chapter 1 presents a brief introduction to the Bengal delta and its estuaries, millennium – scale delta evolution, and century-scale delta development. It also raises the research challenges and defines the objectives of the study. **Chapter 2** provides an overview of planform, topography, main rivers, tributaries and distributaries, floodplain, tidal plains, and estuaries.

The prevailing processes in Ganges-Brahmaputra-Meghna are described in **Chapter 3**. The perspective and the conclusions in the literature vary greatly as a result of the Delta's reaction to various natural and human interventions. Against this background, relevant existing materials on the Bengal delta and deltas worldwide were examined and assessed to have guidance for future investigations that would contribute to a way out of the current crisis and sustainable design of this delta.

Connected to climate change **Chapter 4** discusses briefly global and regional forecasts in the context of diverse studies. Future simulations are constructed based on the forecasts for Bangladesh concerning flow and the release of sediments, subsidence, and the increase of the sea level.

The long-term history of the Ganges-Brahmaputra-Meghna (GBM) Rivers, Bangladesh, from Bahadurabad to the current delta mouth, the Meghna Estuary, was analyzed with a one-dimensional (1-D) process-based morphodynamic model in **Chapter 5**. The impacts of different mean sea levels (MSL), depth of mouth of the river, slopes at river beds, bed ruggedness, and the form of the wide river were assessed using a sensitivity analysis. The 1-D model reproduces the water level in promising agreement with sparse observed water levels data while being extremely simplified and based on approximate assumptions considering the starting bathymetry because of lack of data. Sensitivity calculations indicate that seasonal MSL variations have a substantial influence on the GBM system's hydrodynamic components.

Chapter 6 describes the details of the 2-D model. The precision of hydrodynamic and morphological validation of the 2-D model gave the confidence to reproduce the delta system. Due to the huge system lacking data in the Ganges-Brahmaputra-Meghna (GBM) delta, it is difficult to understand and predict future developments. This chapter states a sediment budget for the GBM delta. This chapter demonstrates the possibilities for the application of a robust modelling system to assess the morphodynamic evolution and sediment budget and pathways.

Chapter 7 presents the conclusions and recommendations of the study.

Chapter 2

Case Study: Bangladesh

This chapter includes the geographical and hydrological description of the Ganges-Brahmaputra-Meghna (GBM) or Bangladesh delta selected for this research. A detailed description of the planform and topography, main river systems and their distributaries, floodplains and tidal plains, and estuaries are made. Finally, a brief description of the delta is made.

This chapter is partly based on:

Akter, J.; Sarker, M.H.; Popescu, I., and Roelvink, D., 2016. Evolution of the Bengal Delta and its prevailing processes. Journal of Coastal Research, 32(5), 1212–1226. Coconut Creek (Florida), ISSN 0749-0208.

2.1 Planform and Topography

Several million years ago, the northeast (NE) portion of the Indo-Australian plate fractured. and sank below the then sea level, resulting in attracting all rivers to meet the sea and forming the present Bengal Basin. The basin is prograding from a NE hinge line (Goodbred and Kuehl, 2000b). Ganges–Brahmaputra (G-B) Rivers are mainly carrying sediment from the fore slope and backslope of the Himalayas, respectively, as shown in Figure 2.1, to form the world's largest fan deposits (Goodbred and Kuehl, 2000b). This deposition of 4 km of deposits at the hinge and more than 10 km at the shelf break (Lindsay, Holiday, and Hulbert, 1991) has created a volume of approximately 1.253x10^7 km^3 for approximately 33x10^6 sqkm of area (Curray, 1994), out of which Bangladesh occupies the major portion, as shown in Figure 2.2.

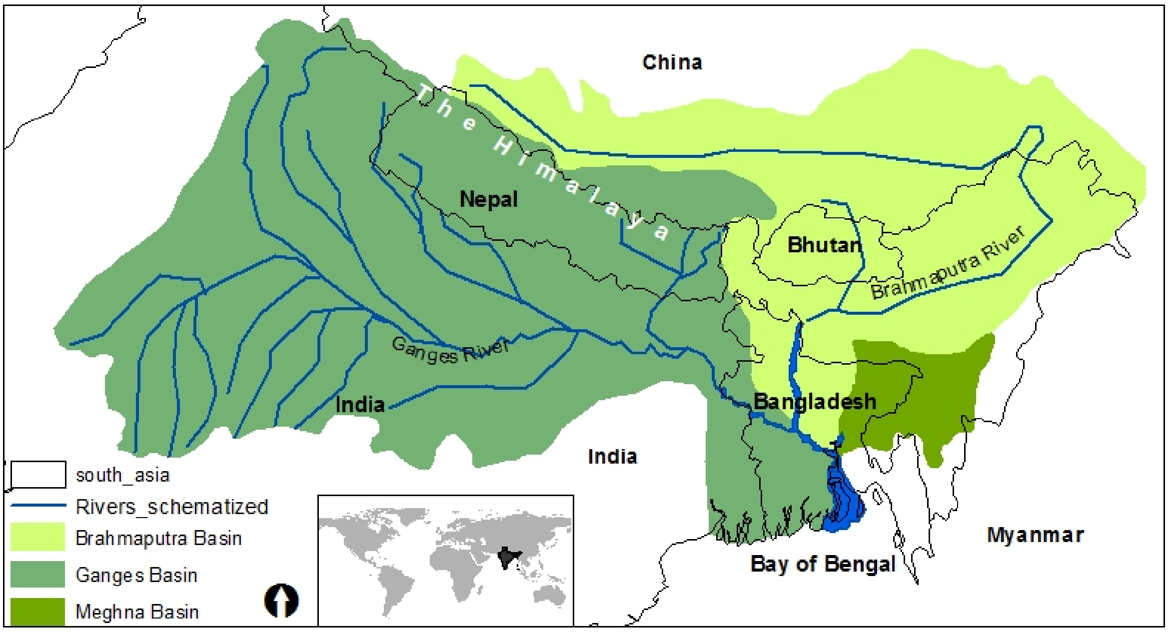


Figure 2.1: Location map of the Ganges, Brahmaputra, and Meghna basins

Geographically, the basin is the entire lowland, which is bounded by the Shillong Plateau on the north, the Burma Arc fold belt on the east, the Bay of Bengal on the south, and the Indian craton on the west (Steckler et al., 2010). The geology of the Bengal delta is mostly characterized by the uplifting of both the Himalaya Mountains to the north and the frontal belt of the Indo-Burman Range to the east, tectonic subsidence, and refilling by rivers that have progressed towards the Bay of Bengal. The basin comprises Tertiary Highlands, the Barind and Madhupur Tracts as uplifted deposits of the Pleistocene (Morgan and McIntire, 1959), and the Comilla Terrace of the Holocene (Goodbred and Kuehl, 2000b). These are the natural controls that regulate river courses shifting or avulsion (Goodbred and Kuehl, 2000b) and subsequently develop the coastal region.

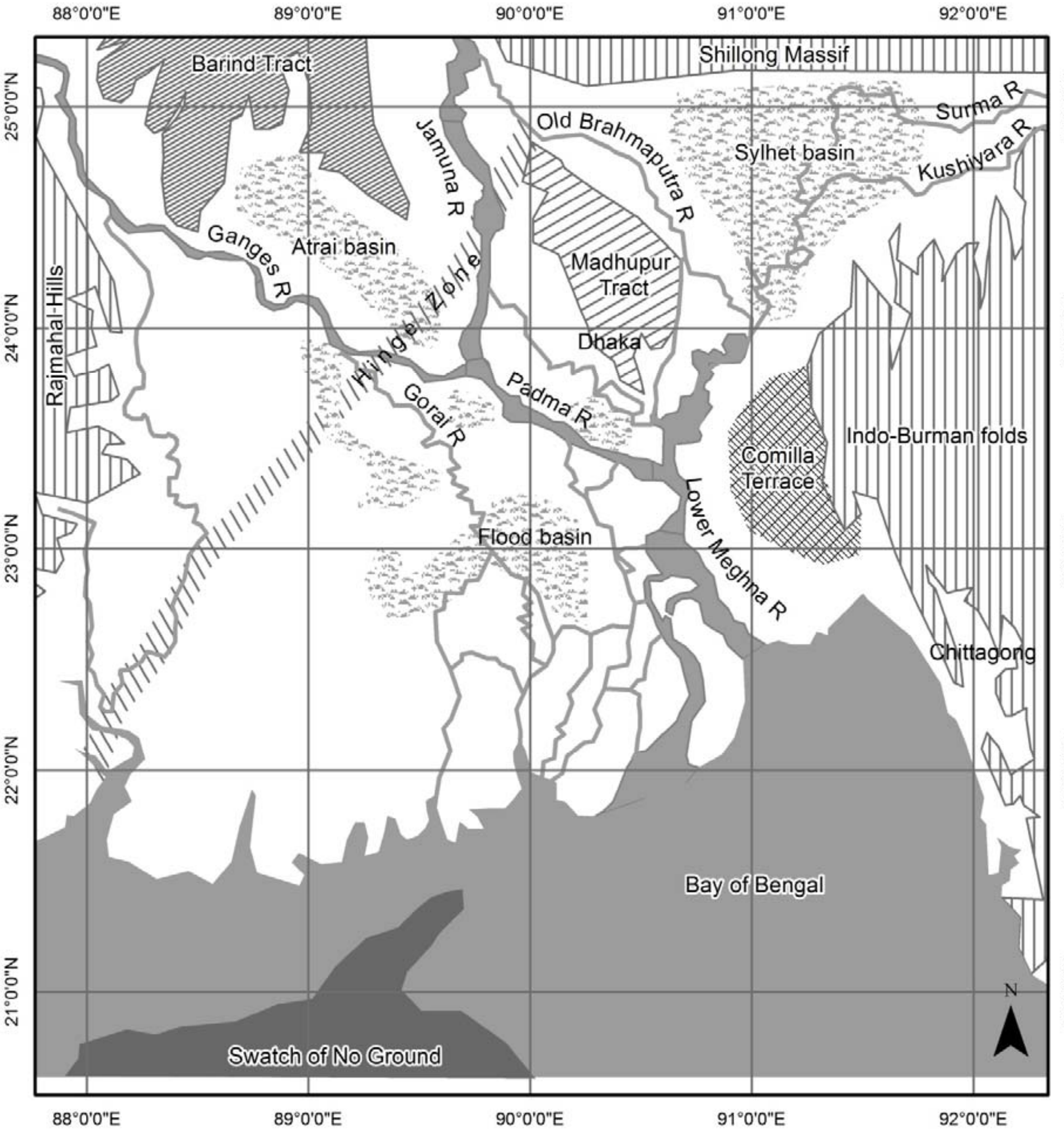


Figure 2.2: Geological setting of the Bengal Delta

2.2 Main Rivers

The Ganges, Brahmaputra, and Meghna, rivers are the main three fluvial sources for conveying sediment for creating this mass basin, about 100,000 sqkm (Figure 2.1), whereas their catchments area are 1,000,000 sqkm, 573,000 sqkm, and 80,000 sqkm respectively. The detailed characteristics of the GBM basins are given in Table 2.1. Figure 2.3 shows the spatial and temporal variation of water discharge of BWDB data during 1980-1999, which has been proven to be ‘realistic’ for this research. The geographical location of Bangladesh makes it the lowest riparian country of fifty-seven transboundary rivers of which fifty-four come from India and three from Myanmar. The GBM rivers, with an average of 1200, 1900, and 4900 mm of rainfall respectively over their catchment area, produce an annual average discharge of about 11300, 20200, and 4600 m^3/s, along with producing sediment at 550, 590, and 13 million ton/year (CEGIS, 2010). Thus, a total of one trillion ($1x10^{12}$) m^3 of water (fourth highest) and sediment at a rate of one billion ($1x10^9$) ton/year (third highest), as the combined flow of the Ganges, Jamuna (the downstream continuation of the Brahmaputra), and Meghna Rivers, are delivered to the Bay of Bengal through the Lower Meghna River.

Table 2.1: Hydro-morphological characteristics of GBM Rivers and their catchments

Rivers	Ganges	Brahmaputra	Meghna
Catchment area (sqkm)	1,000,000	573,000	80,000
Average rainfall (mm)	1200	1900	4900
Annual average discharge (m^3/s)	11,300	20,200	4,600
Sediment (million ton/year)	550	590	13
Average flood discharges (m^3/s)	52,000	70,000	13,700
Maximum discharge (m3/s)	78000	100,000	20,000
D_{50} of the bed material (mm)	0.15	0.2	0.14
Planform	Meandering	Braided	Anastomosing

Source: CEGIS, 2010

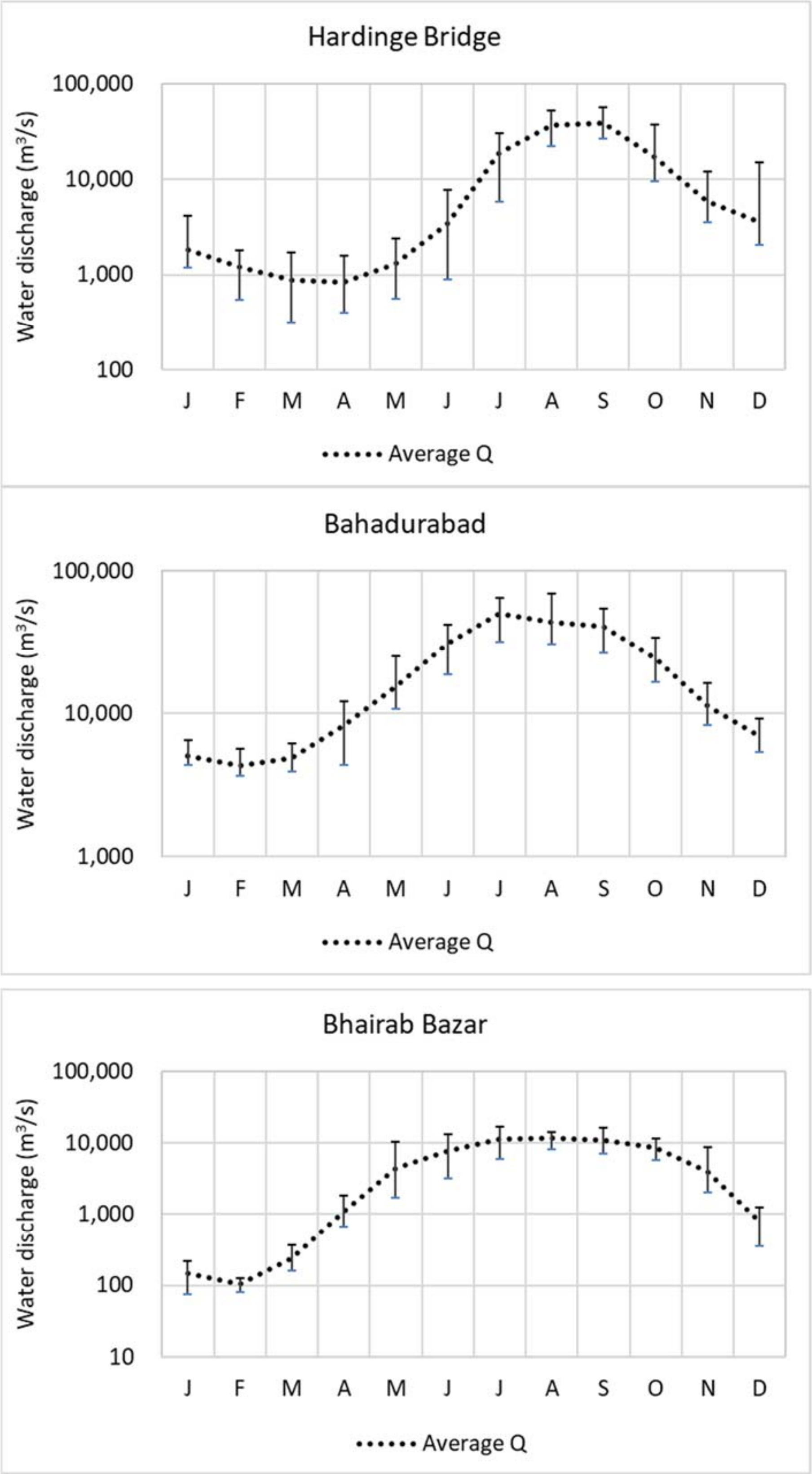


Figure 2.3: Monthly average of water discharge (maximum, average, and minimum) during 1980-1999 in the GBM rivers

The average flood discharges of the Jamuna, Ganges, Padma (the combined flow of the Ganges and Jamuna), and Upper Meghna Rivers are 70000, 52000, 95000, and 13700 m^3/s as measured at Bahadurabad, Hardinge Bridge, Mawa, and Bhairab Bazar, respectively (Sarker et al., 2003). The average low flow discharges are 4250, 600, and 4800 m^3/s for the Jamuna, Ganges, and Padma rivers. The mean sizes of the bed material in the Jamuna (0.20 mm), Ganges (0.15 mm), Padma (0.12 mm), Upper Meghna (0.14 mm), and Lower Meghna (0.09 mm) rivers vary spatially. The planform of the rivers varies from meandering (Ganges) to braiding (Brahmaputra-Jamuna) over space and time, whereas the Padma is wandering and Upper Meghna is anastomosing (Sarker et al., 2003).

2.3 Major Rivers and Distributaries

In the northwestern (NW) region of Bangladesh, Teesta, Dharala, Dhudhkumar, and Atrai are the major rivers that are the tributaries to the Brahmaputra-Jamuna River. The Old Brahmaputra and Dhaleshwari rivers are the main distributaries of the Brahmaputra-Jamuna River. The Old Brahmaputra, combined with Surma-Kushiyara in the NE of Bangladesh form the Upper Meghna River. After merging with the Dhaleshwari and Padma, the Upper Meghna River continues to flow to the sea namely the Lower Meghna River. Gorai and Arial Khan Rivers are the only distributaries of the Ganges and Padma Rivers in the southwest (SW) and southcentral (SC) regions of Bangladesh respectively.

Along with the sediment transported by the GBM Rivers, the other two major distributaries, the Gorai and the Arial Khan, contribute to transporting fluvial inputs to the delta system. The Gorai River delivers annually about 30 billion m^3 of water and 30 million ton of sediment to the bay (EGIS, 2001), and the Arial Khan River supplies about 6 billion m^3 of flow and 25 million ton of sediment every year (Akter, et al, 2013). The Arial Khan River is connected to the Lower Meghna River, which contributes to the present delta-building process. This process is continuing in the Meghna estuary area. There are three major distributaries, the Shahbajpur, Hatiya, and Tentulia Channels, through which most of the water and sediment enter the Bay of Bengal.

2.4 Floodplains

Floodplains that are formed by alleviating rivers are relatively smooth valley floors adjacent to the rivers. It is an area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding. Most of the area of Bangladesh is a floodplain that is formed by the Brahmaputra-Jamuna, Ganges, Teesta, Old Brahmaputra, Surma-Kushiyara, Karatoa-Bangali, Punarvaba Rivers, as shown in Figure 2.4. These rivers are subject to overflow during the monsoon and deposited silt and clay over the floodplain.

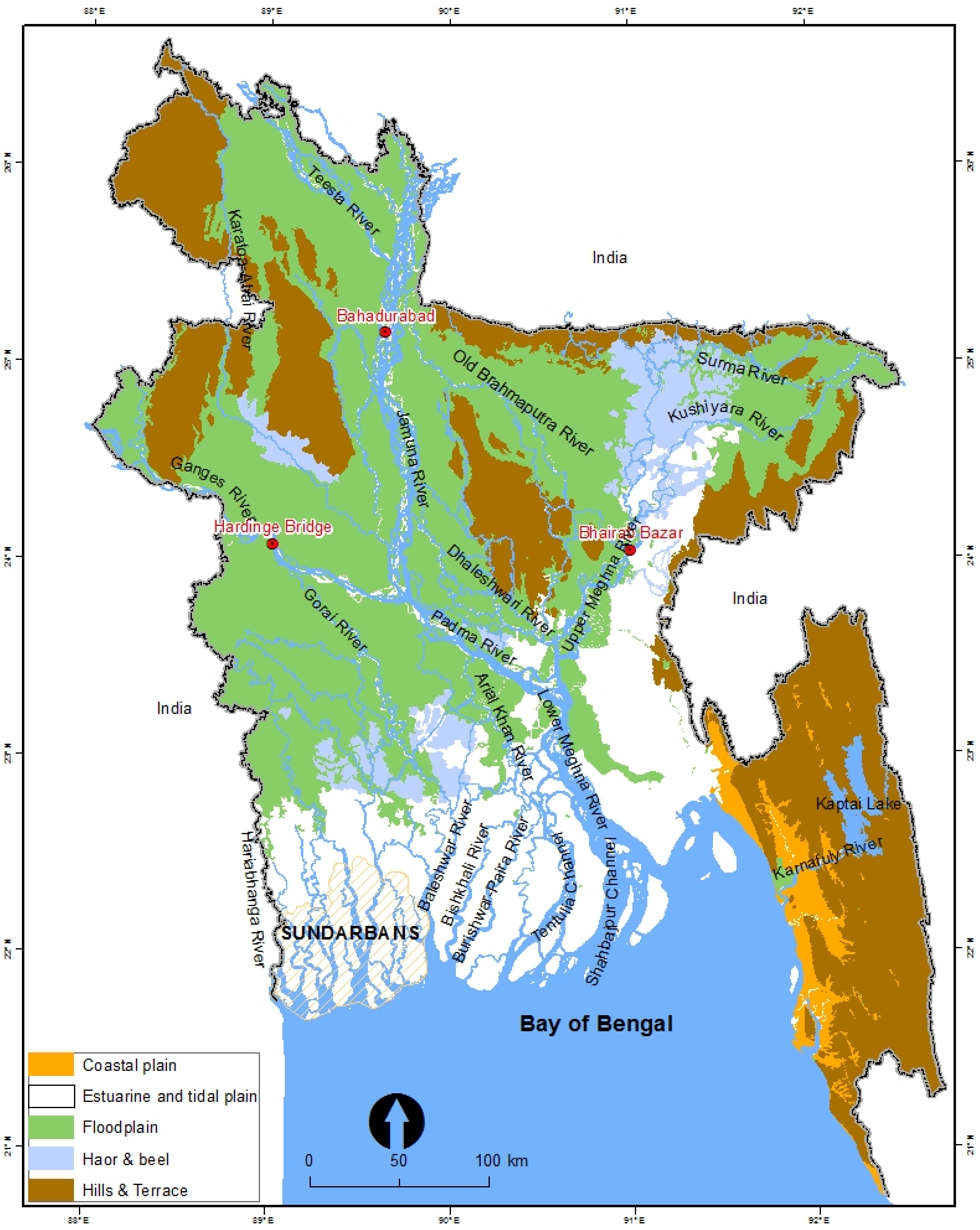


Figure 2.4: Major rivers and their floodplains and tidal plains of Bangladesh

2.5 Tidal Plains

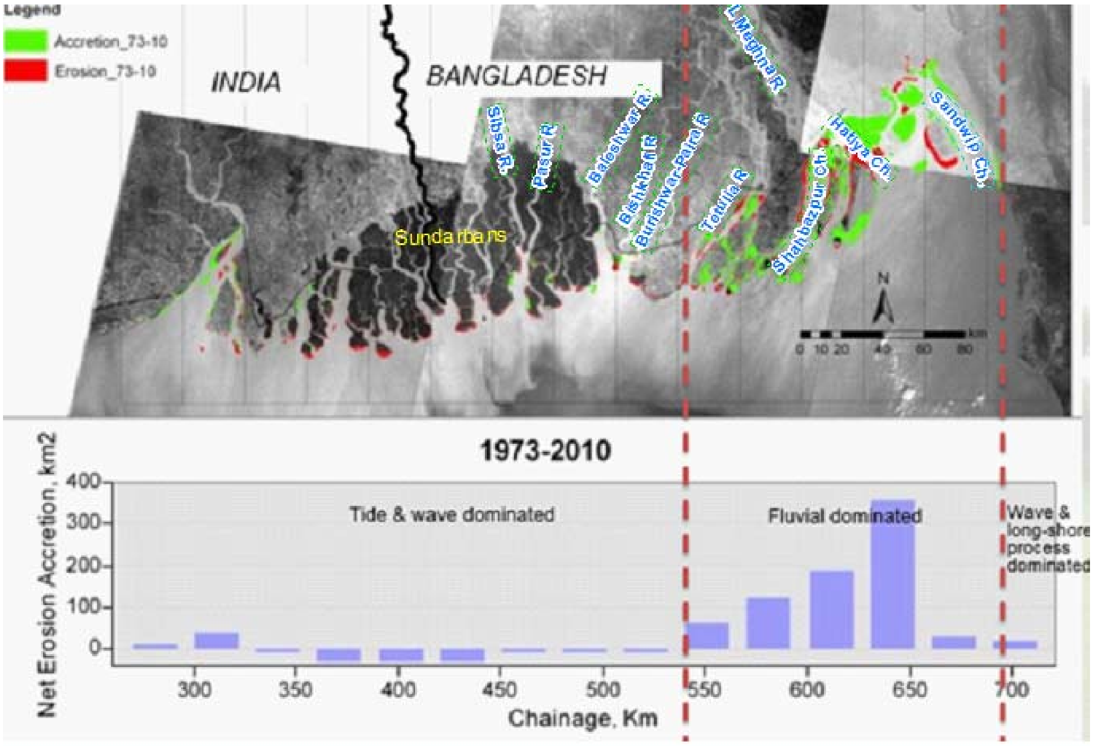
Barua (1991) defines the Ganges tidal plain in between the Hariabhanga River along the Indo-Bangla border in the west and the Tentulia River in the east. This area is supposed to receive freshwater flows from the Ganges and Padma distributaries- Gorai and Arial Khan Rivers and tides from the Bay of Bengal. The western half of this tidal plain is characterized by a tropical mangrove forest 'Sundarbans'. Being slightly above mean sea level (MSL), this area is flooded during high spring tides, although flood embankments are constructed in most of the area.

Presently the delta building activities are active on the eastern side of this area, Meghna estuary, due to huge sediment sources from the GBM Rivers system. Mainly the right bank distributaries of the Ganges and Padma Rivers, the Gorai and Arial Khan rivers respectively, are supplying the fluvial flow and sediment into this tidal plain. In the southwest region of Bangladesh, which is a moribund delta now, active delta-building activities have been suspended probably several hundred to thousands of years ago. The northern margin of this area comprises of Old Ganges floodplain, the middle part consists of the Gopalganj-Khulna depression, and the southern part is the tidal plain. The middle and the southern parts of this region are susceptible to being eroded every year.

2.6 Estuaries

Estuaries, very much unique in each of their physical and biological attributes, are considered to be the transition zones between the freshwater and marine water habitats, where freshwater meets saltwater. Along with many small estuaries, the Passur-Sibsa, Baleshwar, Bishkhali, Burishwar-Paira, Meghna, Muhuri, Karnafuly, Matamuhuri, Sangu estuaries are mentioned-worthy. Out of these estuaries, flow distribution in the Meghna Estuary is determined by the combined action of tide and fluvial flow from the GBM Rivers. On the other hand, western estuaries are moribund estuaries that are wave and tide-dominated, and the eastern estuaries are marine wave and longshore process-dominated, as shown in Figure 2.5.

Tides are semidiurnal, with a slight diurnal inequality, along the coast of the Bengal Delta (including the Indian part), and the average tidal range varies from 1.5 m in the west to more than 4 m at the NE tip of the Meghna estuary. However, the Meghna estuary is a meso-tidal estuary, where the tidal range varies between 2 and 4 m (MES II, 2001).



Source: (Akter, et.al. 2016)

Figure 2.5: Estuaries and their net erosion-accretion

2.7 Climate

Bangladesh is characterized by a subtropical monsoon climate with wide seasonal variations in temperatures, rainfall, and humidity. Presently, three seasons are distinctive in Bangladesh: a hot and humid period from March to June; a cool and rainy monsoon season from June to October; and a cool and dry winter from October to March. Generally, maximum summer temperatures range between 30°C and 40°C. January is the coldest month when the average temperature is about 10°C. The climate is one of the wettest in the world. Heavy rainfall is characteristic of Bangladesh. Except for the relatively dry western region of Rajshahi, where the annual rainfall is less than 1600 mm, most parts of the country receive at least 2000 mm of rainfall per year. Because of its geographical location, just south of the Himalayas foothills, where monsoon winds turn west and northwest, the regions in northeastern Bangladesh receive the greatest average precipitation, sometimes it is recorded as high as 4900 mm in a year. About 80 percent of Bangladesh's rain falls during the monsoon season.

2.8 Summary

The Ganges, Brahmaputra, and Meghna rivers are the major three fluvial suppliers of sediment for building this 100,000 sqkm mass basin, GBM delta. As the combined flow of the Ganges, Jamuna (the downstream continuation of the Brahmaputra), and Meghna Rivers is delivered to the Bay of Bengal via the Lower Meghna River, a total of one trillion ($1x10^{12}$) m3 of water (fourth highest) and sediment at a rate of one billion ($1x10^{9}$) ton/year (third highest).

The Teesta, Dharala, Dhudhkumar, and Atrai rivers are important tributaries of the Brahmaputra-Jamuna River in Bangladesh's northwestern (NW) area. The primary tributaries of the Brahmaputra-Jamuna River are the Old Brahmaputra and Dhaleshwari rivers. The Upper Meghna River is formed by the confluence of the Old Brahmaputra and the Surma-Kushiyara rivers in the northeastern part of Bangladesh. After joining the Dhaleshwari and Padma rivers, the Upper Meghna River flows to the sea as the Lower Meghna River. In the southwest (SW) and southcentral (SC) areas of Bangladesh, the Gorai and Arial Khan Rivers are the only distributaries of the Ganges and Padma Rivers, respectively.

The majority of Bangladesh is a floodplain produced by the rivers Brahmaputra-Jamuna, Ganges, Teesta, Old Brahmaputra, Surma-Kushiyara, Karatoa-Bangali, and Punarvaba, which overflow during the monsoon and deposit silt and clay across the floodplain. The Ganges tidal plain is between the Hariabhanga River in the west and the Tentulia River in the east, near the Indo-Bangla border. This region is expected to get freshwater flows from the Ganges and Padma distributaries, the Gorai and Arial Khan Rivers, as well as tides from the Bay of Bengal. The western side of this tidal plain is dominated by a tropical mangrove forest known as 'Sundarbans.' Because it is slightly above MSL, this area floods at high spring tides, although flood embankments have been built throughout the majority of the area.

Estuaries, which are distinct in their physical and ecological characteristics, are thought to represent the transition zones between freshwater and marine water environments, where freshwater meets saltwater. The Passur-Sibsa, Baleshwar, Bishkhali, Burishwar-Paira, Meghna, Muhuri, Karnafuly, Matamuhuri, and Sangu estuaries, among many others, are noteworthy. Out of these estuaries, the combined effect of tidal and fluvial flow from the GBM Rivers determines flow distribution in the Meghna Estuary. Western estuaries, on the other hand, are moribund estuaries characterized by wave and tide, and eastern estuaries are controlled by marine wave and longshore processes.

Bangladesh has a subtropical monsoon climate with large seasonal fluctuations in temperature and rainfall. Bangladesh is known for its heavy rains. Except for Rajshahi's extremely arid western area, where annual rainfall is less than 1600 mm, most sections of the nation receive at least 2000 mm of rain each year. Northeastern Bangladesh receives the most average precipitation due to its geographical location just south of the Himalayan foothills, when monsoon winds shift west and northwest. During the monsoon season, around 80% of Bangladesh's rain falls.

Chapter 3
Prevailing Processes

This chapter describes the prevailing process in the Ganges-Brahmaputra-Meghna (GBM) system. There are significant differences in opinions and widely varying findings in the literature on the response of the delta to different natural and human interventions. Against this backdrop, relevant available literature on the Bengal delta and deltas elsewhere in the world is reviewed and evaluated to provide direction for future research that would help to form a way out of the present situation and into sustainable planning for this delta.

This chapter is partly based on:

Akter, J.; Sarker, M.H.; Popescu, I., and Roelvink, D., 2016. Evolution of the Bengal Delta and its prevailing processes. Journal of Coastal Research, 32 (5), 1212–1226. Coconut Creek (Florida), ISSN 0749-0208.

3.1 Characteristics of Bengal delta and estuaries

Geo-morphologically, estuaries of the Bengal delta are classified as river delta estuaries. These are found at the mouth of large rivers and are characterized by semi-enclosed bays, and channels and are formed by river shifting silt deposition. Based on water circulation and stratification, the Meghna estuary is classified as well-mixed, where tides play the dominant role to make a well-mixed to-to-bottom environment and the salinity is relatively high. Based on ecosystem energetic estuaries, all the south-facing estuaries of the delta are classified as natural tropical coastal ecosystems of high diversity. Temperature, salinity, and other physical stresses are low in these estuaries and hence invite a great deal of diversity within many species. Based on freshwater discharge, the estuaries are positive, where freshwater runoff is greater than evaporation.

Although physical environment, i.e. geomorphology, climate, salinity, and the availability of freshwater, primarily control the estuarine ecosystem; other abiotic features; i.e. oceanic forces, quantity of fresh water, the water circulation pattern, variability of salinity, tides, depth, geo-morphological changes, are important in determining the specific nature of estuaries (Day et.al., 1989).

Meghna Estuary, which is presently the active delta building system of the Bengal basin. It is the easternmost of the delta. The estuary conveys the combined discharge of the Ganges-Padma, Brahmaputra-Jamuna, and Meghna rivers to the Bay of Bengal. As a result, approximately one trillion m^3 water discharge per year (7 m of the water column over 147,570 sqkm lands of Bangladesh) and more than one billion ton of sediment per year (3.5 mm of sediment column over Bangladesh) are transported through the area (Akter et.al., 2016).

3.2 Assam Earthquake 1950

Drastic changes in the G-B basins were observed in the past caused by major seismic activities (Gupta et al., 2014). Seismic events in the Brahmaputra basin (Goodbred et al., 2003) could also change the sediment scenario and its responses. The 1950 Assam earthquake, with a magnitude of 8.5 Richter scale, caused huge changes in the river system and the delta plains. Sarker et al. (2011) indicated that sediment generated by the 1950 earthquake, which was transported through the Brahmaputra, caused huge sedimentation in the Meghna estuary. The fine fraction of sediment rushed into the estuary within a few years, whereas, the coarse fraction (fine sand) propagated downstream as sediment wave and took nearly five decades to complete its journey to the Bay (Sarker and Thorne, 2006; Sarker, 2009). Sarker et al.

(2013) indicated that the rate of land reclamation in the Meghna estuary was mainly a result of sediment carried to the estuary which was generated after the 1950 Assam earthquake. The progradation of the delta affected the water level in the Shahbajpur channel (Figure 2.5) and also in the Lower Meghna River. Analysis of monsoon water levels of different gauging stations in this system shows a high increase in the Shahbajpur channel and a small increase in the Lower Meghna River (CEGIS, 2010). However, during the preceding decade, water levels of all these stations showed a receding trend, the reason for which probably lies with the sediment input in the system/changes in local morphology of the downstream channels. Unfortunately, there is no sediment data available for this period. Sarker (2009), however, indicated that as the trailing edge of the sediment wave has already entered the Bay, it could have caused a sediment deficit in this area and a temporary phase of channel degradation.

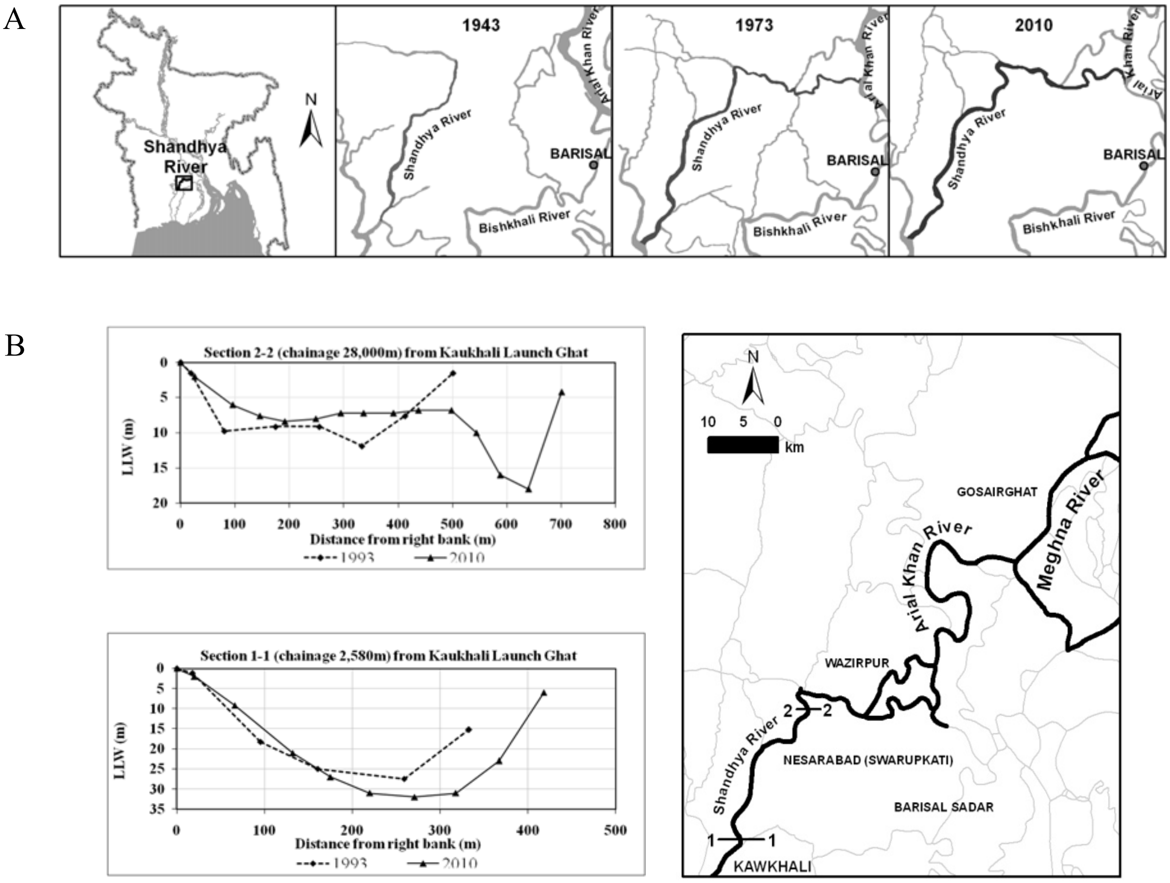
3.3 River Shifting and Avulsion

Buffington (2012) stated that rivers exhibit comprehensive responses (ranging from a small-scale adjustment of channel characteristics including grain size, width, and depth, to large-scale alteration of reach morphology and planform pattern) to changing contributions of water, sediment, and vegetation over human time scales (<100 years). Not only watershed features (including topography, discharge due to intensive rainfall, sediment supply due to tectonic events like earthquakes and landslides, and vegetation cover, as described in Buffington, 2012), but also localized sea level and its associated tidal forcing and circulation process, especially in an active delta building system, control river morphology. Accordingly, it is obvious to observe few changes in the Bangladesh delta on a few decade scales. A qualitative sequence of long-term shifting and recent shifting of the main rivers in this region was firstly described by Fergusson (1863) and Williams (1919). But their suggested time order could not be related to known changes in conditions bounding the terrestrial component of the delta, such as sea-level changes (Akter, et. al., 2016). Whereas, the sequence of shifting of the G-B Rivers suggested by Umitsu (1993) seems somewhat similar to that described by Williams (1919).

In millennium scale development of the G-B delta from the late Quaternary and extending through the Holocene was presented by Goodbred and Kuehl (1998, 2000a, b) based on borehole data analysis. In century-scale changes, the major change in the last two centuries was the Brahmaputra avulsion from the east of the Madhupur Tract to the present course of the Jamuna River from 1776 to 1830 (Hirst, 1916). As a response and adjustment to the avulsion, other rivers change their courses (Sarker, 2009, Sarker et al, 2013; Akter et al, 2016).

Observation since the 1970s reveals several changes in the southwest flowing distributaries. During this period, the Gorai River has been reported to divert its flow from 50% to 95% to its southwest directed distributary, the Nabaganga River (EGIS, 2001). Many of the distributaries generated from the Lower Meghna and/or Arial Khan river are developing in terms of river depth from the cross-sectional data and width from the satellite images and historical maps analysis. Sarker *et. al.* (2013) reported the Shandhya River, as shown in Figure 3.1 (A), as a newly developed south-westerly flowing distributary of the Arial Khan and Lower Meghna rivers. Based on image analysis the Shandhya River was seemingly developed between 1943 and 1973. Most of the cross-sections made from the Hydrographic survey charts of the Bangladesh Inland Water Transport Authority (BIWTA) show an increase in the conveyance area of the respective sections, as shown in Figure 3.1 (B). However, progradation-related avulsions are supposed to have occurred in this delta system. Hajek and Edmonds (2014) demonstrate that floodplain morphodynamics would determine rivers' relocation and associated floodplain erosion and deposition.

Moreover, most of the distributaries of the Ganges during the 18th and 19th centuries flowed in the southeast direction. But presently most of the distributaries are found to be flowing in the southwest direction, like- the flow of the Gorai-Madhumati River started to flow southwest along with a few other distributaries from the Lower Meghna and Arial Khan rivers since the mid-20th century. The Gorai River is reported to divert 90% of the flow to the southwest directed channel.

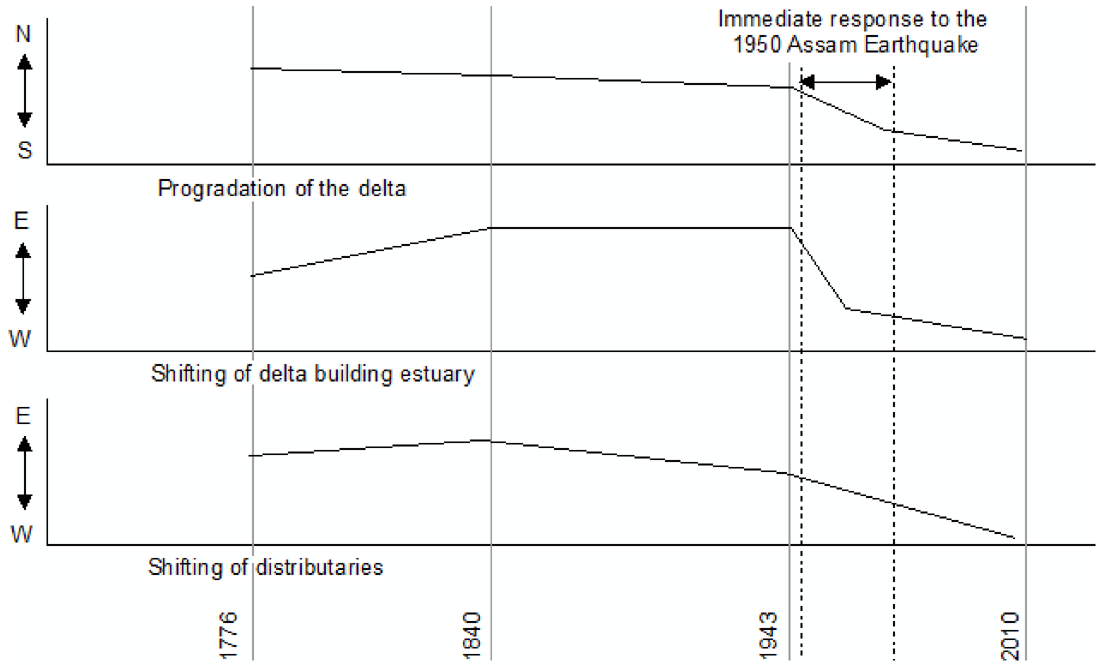


Source: Sarker et. al., 2013

Figure 3.1: A) Evolution of the Shandhya River and B) its changes in cross-profile between 1993 and 2010.

3.4 Delta Shifting

Delta shifting unfolds over relatively long time scales, probably century to millennium scale unless otherwise, human intervention does not interrupt the natural process. On the contrary, river avulsion may be observed ranging from 28 years for the Kosi River in India to 1400 years for the Mississippi River in the United States (Slingerland and Smith, 2004). Although, sediment supply from the channel to the floodplain and excess shear stress in overland flows have important influences on channel avulsion (Hajek and Edmonds, 2014) and following delta shifting in the long run. In line with this, the Bengal delta is comparatively less intervened and a huge pile of sediment every year might put an option for shifting the delta.



Source: Sarker et. al., 2013

Figure 3.2: Qualitative shifting of the delta and its associated distributaries

Many kinds of literature have mentioned the shifting of the Bengal delta (FAO, 1988; Sarker *et al.*, 2013; Akter, et. Al., 2016; Fergusson, 1863). Sarker *et al.*, 2013 reported that the delta is shifting at different locations as the delta building process is continuing. Based on maps and images, Sarker *et al.*, 2013 qualitatively assessed delta progradation in the north-south direction, shifting of the delta building estuary, and also shifting of the direction of the distributaries along the east-west direction, as shown in Figure 3.2. According to Sarker *et al.* (2011), net accretion in the Meghna estuary was only 4.5 sqkm/y during the period 1776 to 1943, which was increased to 42 sqkm/y from 1943 to 1973, and was reduced again to 17 sqkm/y from 1973 to 2013. Although, the Assam earthquake in 1950 is likely to cause huge accretion in the 1950s and 1960s (Sarker, 2009); and Akter, et. al., 2016), that in turn resulted in the delta progradation and thus accelerated the shifting process (Sarker *et al.*, 2013).

From the old imageries of the late 18th century, it is found that the Ganges River was active in a separate estuary in developing the delta, other than the separate estuary in the east from the combined flow of the Brahmaputra and Meghna. The middle part of the delta was directly getting fluvial inputs through the Ganges estuary separately along with its active distributaries. When they merged, the easternmost part of the delta was built and accreted a huge amount of land in the southern boundary of the Noakhali. The easternmost channel of the Lower Meghna estuary has been abandoned and has become a part of the mainland. This might be resulting in the initiation of a reverse shifting of the active delta building estuary towards the west since the last century. However, the active delta building estuary and associated distributaries have been shifting their courses. Huge sediment caused by landslides during the 8.5 Richter Scale Assam Earthquake in 1950 played a pronounced role in accelerating the delta shifting process.

3.5 Tidal Plain Sedimentation

In an active fluvial environment, sedimentation would be expected through recurrent floods. Sarker, et. Al., (2013) exhibited the tidal plain sedimentation in the active delta building part by comparing two sets of Digital Elevation Models from the 1950s and 1990s. They reported the topography of the delta characterized by a very gentle slope. Figure 3.3 indicates that a large part of this delta lies 2m below the PWD datum (about 1.5 m above Mean Sea Level). Zero meter (0.00 m PWD) references 0.46 m below Mean Sea Level (MSL). The elevated areas at the northwestern tip have a higher gradient and mainly consist of the Ganges floodplain, with an elevation greater than 5 mPWD. The Gopalganj-Khulna beels (which are basin-like wetlands formed by surrounding river levees and have static water during monsoon) are the most low-lying areas having minimum elevation below the MSL. These beels are mainly the low floodplains among the major rivers, the Arial Khan, Gorai, Bhairab, and Kabadak, where sediment could not reach in recent decades. Sarker, et. Al., 2013 mentioned that a big depression, clearly visible in Rennel's map (1976), was dissected by recent and old courses of the rivers. The southern part of the beels is at a higher elevation due to the tidal sedimentation from the sea. And hence the terrain has a reverse slope to the south than from the northeast.

The west to east aligned section A of Figure 3.3 across the Gopalganj Khulna beels indicates that the Gopalganj-Khulna beels start from 30 km west margin and spread up to 90 km towards the east, dissecting by three rivers. But after 120 km from the west margin, the characteristics of the tidal plain are observed until it cuts the Lower Meghna River at 155 km. After the section from 120 km, the wide and elevated ridge formed by the Arial Khan and the Lower Meghna rivers has an average elevation of 3 mPWD.

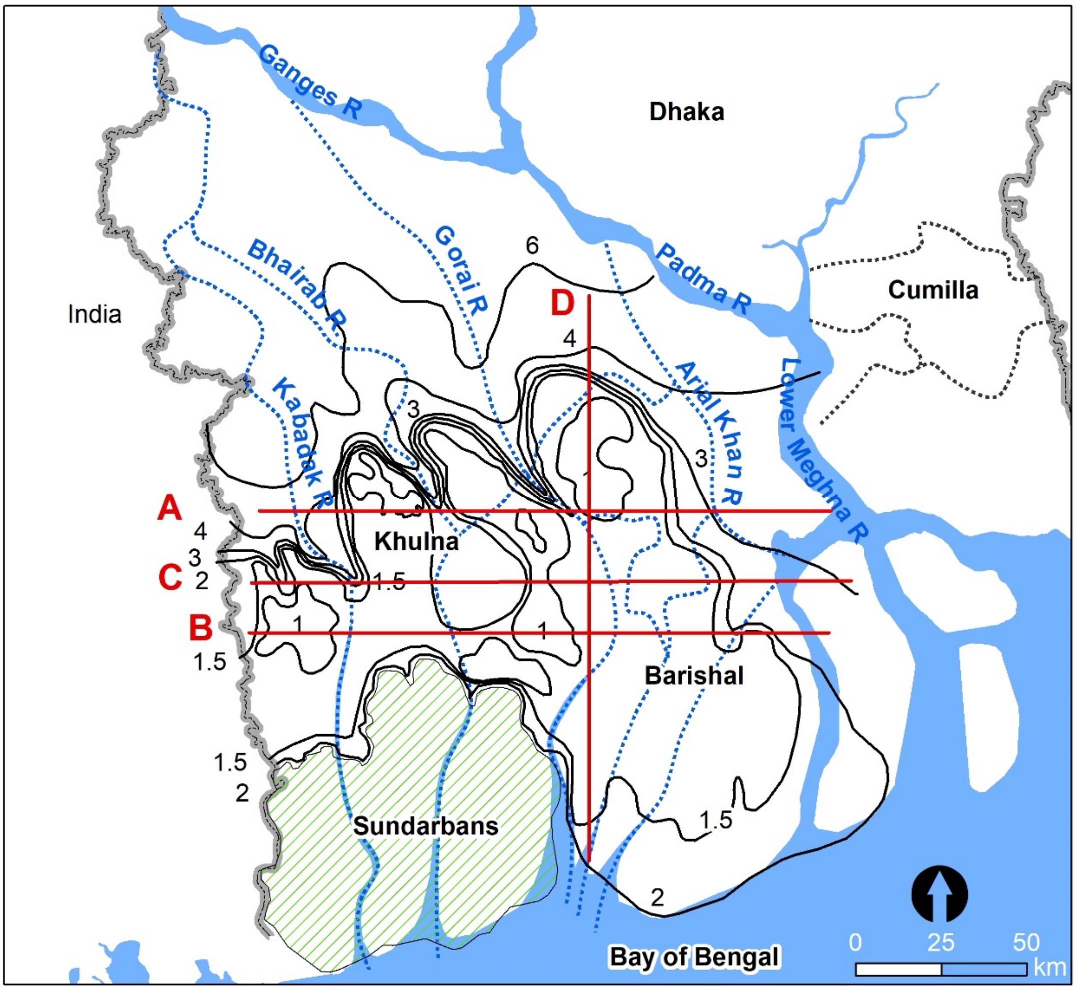


Figure 3.3: Contours of elevation are in mPWD based on the DEM of the 1950s and the river courses based on the 1943 map are shown by the dashed line

Along with Section B, 50 km south of Section A, a few parts of the westward sloping terrain were elevated by 1 to 2 m by the natural levees of rivers Kholpetua, Kabadak, and Brairab. The rest of the section in the east is in the Ganges tidal plain, where there is no distinguishable river levee that can be compared with the tidal basin. The existence of the beels area is hardly be found in this section. But the higher elevation, about a level of 3 mPWD, in the east with a wide ridge is formed by the Lower Meghna River.

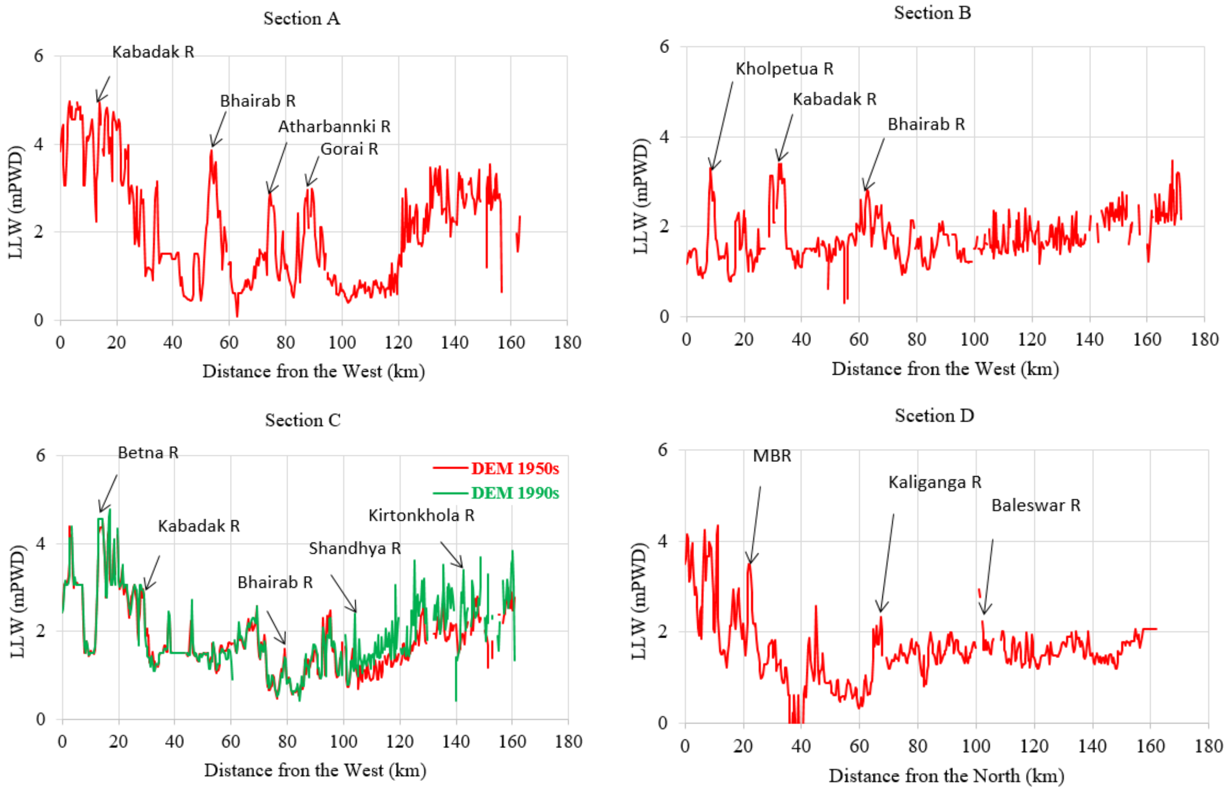


Figure 3.4: Terrain cross-profile Section A, Section B, changes in elevation along Section C from the 1950s to the 1990s and north and south cross-profile along Section D, sections are shown in Figure 3.3.

The north-south aligned Section D starts from the Active Ganges floodplain, which has a similar elevation to Section A. The Gopalganj depression is visible after 20 km from the north margin with a minimum elevation below MS and it spreads for 50 km. The northern part of the depression is elevated a bit by the fluvial inputs by the then active Kumar River along with the Madaripur Beel Route (MBR). After the natural levee of the Madhumati River, which is the boundary of the Gopalganj-Khulna depression to the south, the rest of Section D lies in the Ganges tidal plain, having almost a very flat terrain elevation of below 2 mPWD.

A comparison of two DEMs of the 1950s and 1990s along Section C clearly shows the change of elevation in those four decades. Hardly any change was observed in the Ganges floodplain and Gopalganj-Khulna beel areas up to 100 km from the eastern margin. A prominent change was detected at the eastern margin of section C with a wide ridge formed by the Arial Khan and the Lower Meghna River. Sarker, et. al., 2013 calculated the average rise of elevation of the 40 km eastern length is 0.30 m during that four decades. They concluded that delta progradation during the period might have contributed to a rise in the level of the tidal plain.

This evident change might have contributed to Shandhya River development in southwest Bangladesh.

3.6 Delta Progradation

Delta progradation only, other than subsidence, human intervention, and overall climate change, will have significant effects on the estuarine morphological regimes. Because delta progradation will increase the water level immediately upstream as an early response. Presently, the Meghna Estuary is the active delta building estuary of the Bengal delta. Significant changes are observed since the 1950s. The eastward course of the Lower Meghna River was abandoned during the 1950s (Hatiya Channel shown in light blue lines found in 1943, shown in Figure 3.5) that might be a consequence of the 1950 Assam Earthquake. Cross-dam construction by the Bangladesh Water Development Board (BWDB) might have accelerated the sedimentation process in the then Hatiya Channel. As a consequence, this abandoned channel might have had some effects on the delta progradation. The unavailability of satellite images along with water level, salinity, and cross-sectional profile of channels before the 1970s, make it challenging to find the impact of the abandoned channel in the estuarine morphodynamics.

A comparison of Satellite images of 1984 and 1996 indicates the rapid declination of the Hatiya Channel width from 12 km to 6 km. Furthermore, Land Reclamation Programme in the 1980s and Meghna Estuary Study (MES) in the 1990s reported that the conveyance area of the Hatiya channel below 0 mPWD datum was reduced more than 20%, whereas the flow area of Shahbajpur Channel was increased to the same extent during the same period (MESII, 2001). MES II (2001) also showed that 10% and 70% of monsoon flow passes through the Hatiya and Shahbajpur Channels respectively, measured in Chandpur.

If the delta progradation along the Meghna estuary occurs, it would have an impact on the water levels in the Lower Meghna River. Apparently, as a morphological immediate response, the water level would show an increasing trend. The response of delta progradation along the Shahbajpur Channel and Lower Meghna River is shown in Figure 3.6. Monsoon average water level data at stations Char Tazumuddin, Nilkamal, and Chandpur (locations are shown in Figure 3.5) show an increasing trend, as shown in Figure 3.6. The rate of an increasing trend at Tazumuddin (Location A) is higher in comparison to Nilkamal (Location B) and Chandpur (Location C).

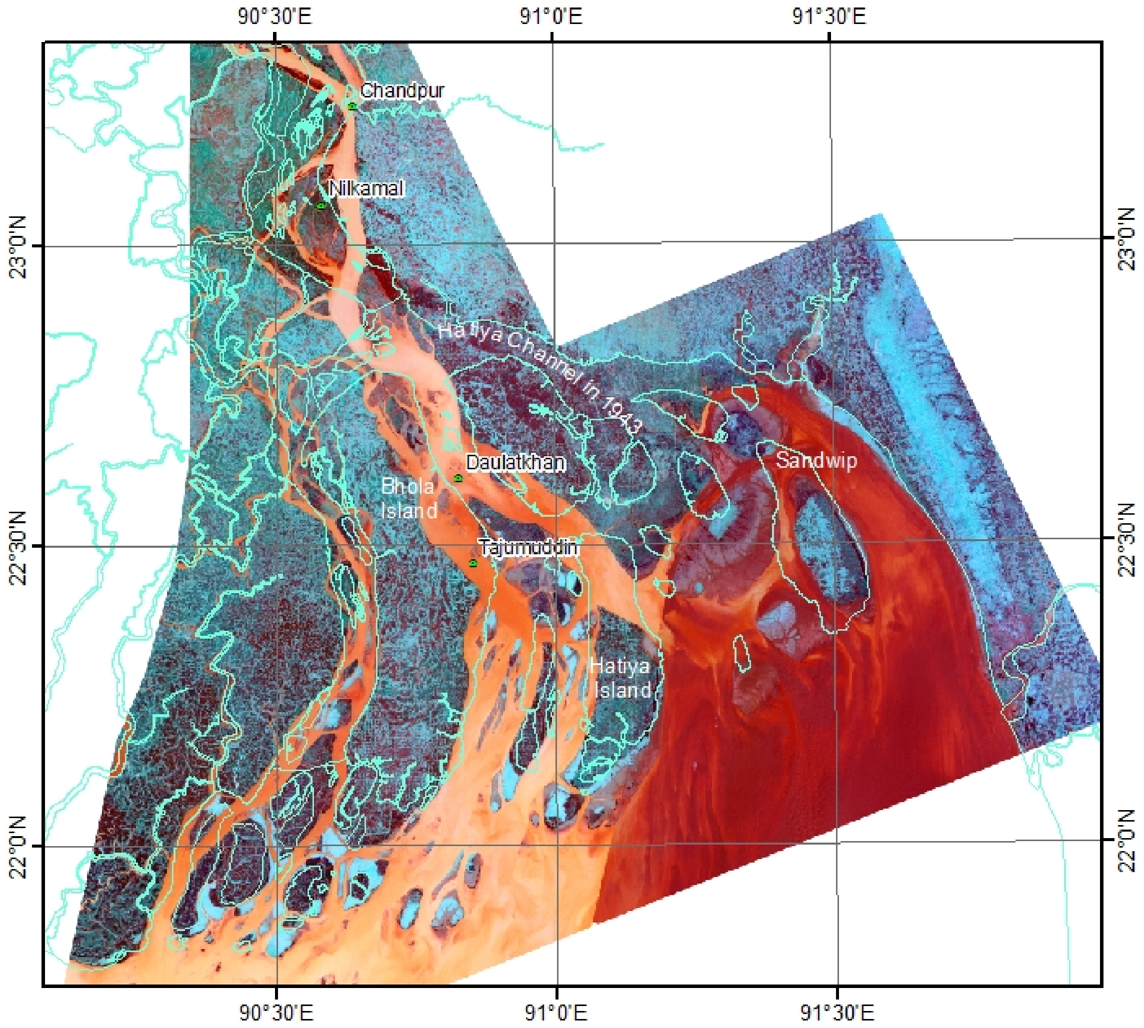


Figure 3.5: Map showing the rivers' courses in 1943 (in light blue lines) on satellite images of 2012.

Sarker et al 2021, shows that the decade-scale displacement of the southern tips of Bhola, Hatiya, Sandwip is considered as delta progradation. Progaradation at Bhola is 50 km. Bhola gained 50 sqkm between 1943 and 1973, when the Meghna estuary had massive net accretion, whereas Hatiya and Sandwip lost 50 and 135 sqkm, respectively. A significant volume of sediment pushed the islands southward by prograding the coastline (connected to the mainland) many kilometers towards the Bay of Bengal. When primary distributaries run along the west or east margins of islands, erosion is more likely to occur. The Bhola and Hatiya islands' southernmost points moved many kilometers towards the bay. Large distributary waterways flowed over the islands' east and/or west sides, causing significant coastal erosion.

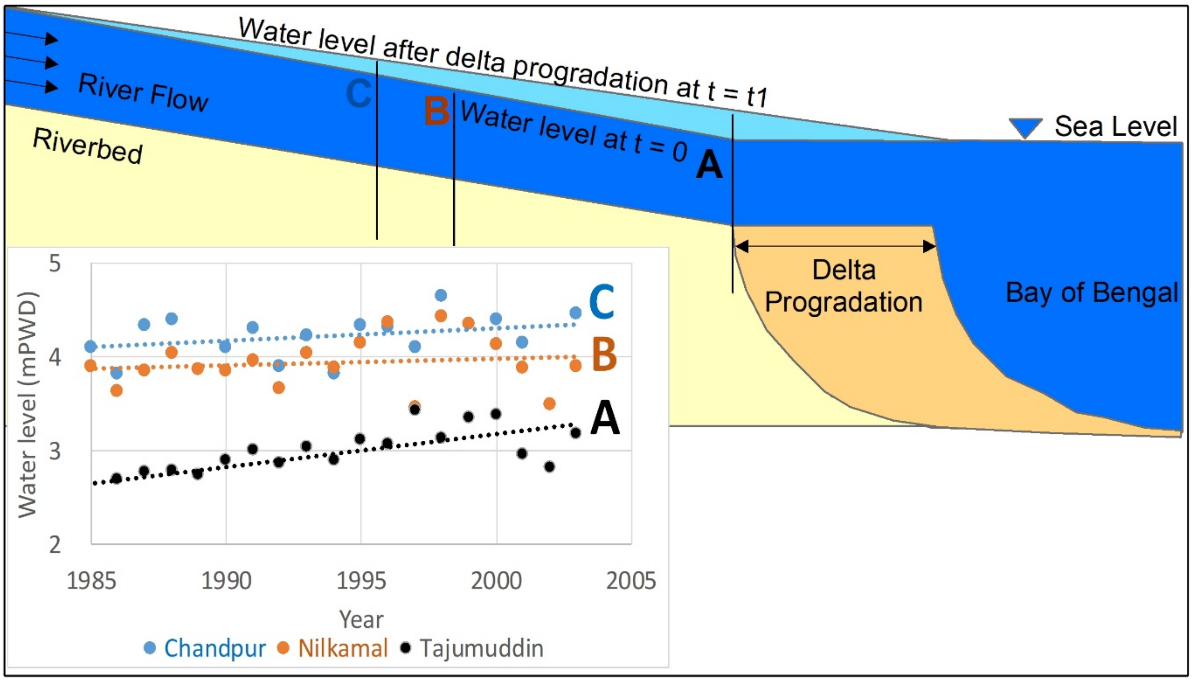


Figure 3.6. Schematic diagram showing the trend of increasing monsoon average water level as a response to delta progradation along the Lower Meghna River and Shahbajpur Channel

Figure 3.7 shows the movement of the islands in the Meghna Estuary according to 1776 Rennel's, 1840 Tasin's, and 1943 Topo Map. This investigation was done only for the major and stable islands. The southern tip of every island is moving southerly with different progradation rates depending on its local morphology. To depict the evolution more clearly, the changes of Monpura island (located between Bhola and Hatiya) has been moved. The morphodynamic evolution of the islands was governed by the abandonment, decline, and enlargement of surrounding distributary channels over time (Figure 3.7). In 1840, the islands of Bhola and Hatiya islands began to curve southwest towards their southernmost points. The southern points' migratory paths were curving towards the Oceanic Trench (close to Hiron Point in Sundarbans). The migration processes were not present at Sandwip island.

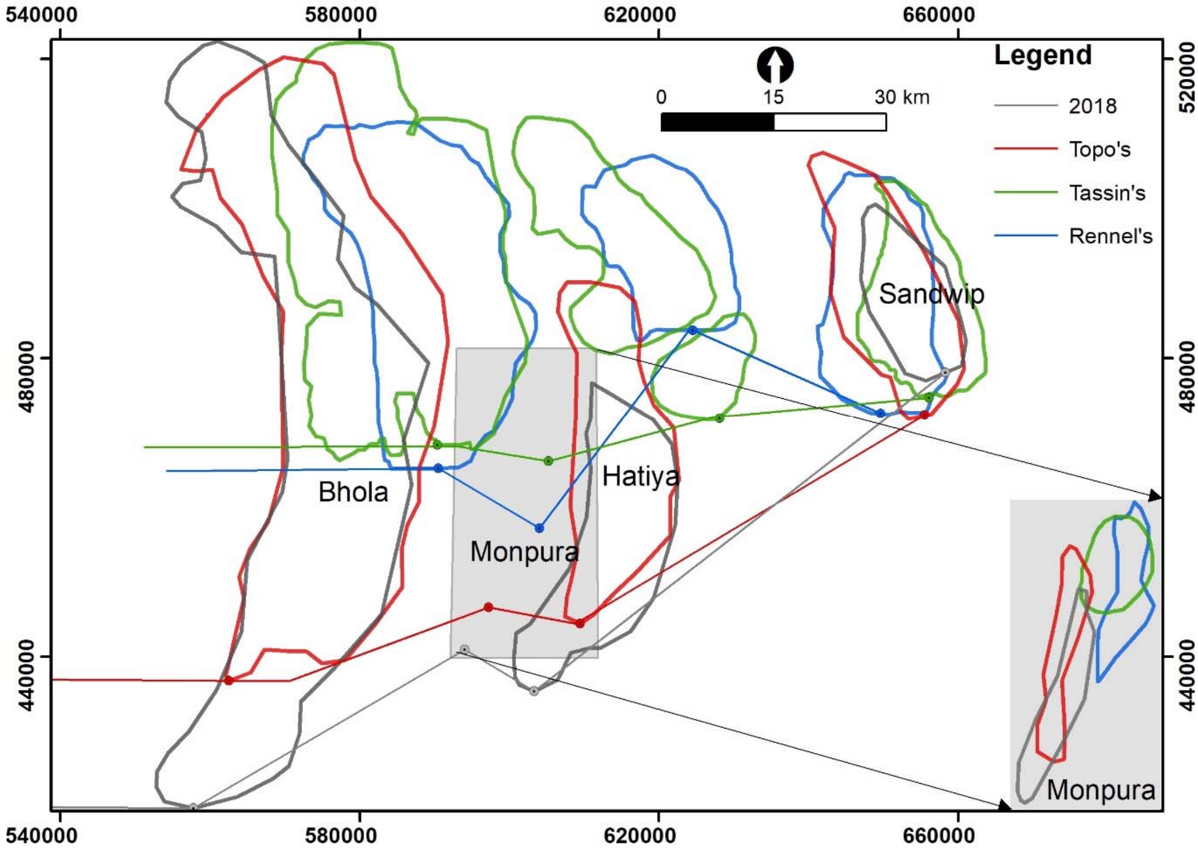


Figure 3.7: Century-scale stability of the islands and delta progradation.

3.7 Erosion/ Accretion Process

3.7.1 Process in the G-B-M Rivers

Non-cohesive sediment at the riverbanks of the Jamuna (Thorne et al., 1993) has caused huge erosion every year and allows the river to be the most dynamic. As the present course of the Jamuna is a new encroachment since the early 19th century, erosion is naturally expected during its developing phase; although it causes unlimited suffering to the char and riverbank settlers; Analysis of banklines of 1973 and 2009 indicates about 900 sqkm of the floodplain was eroded, whereas only 100 sqkm of the floodplain was acquired. Hence erosion has been a dominating process with nine-folds, although the rate of erosion varies year to year (Figure 3.8). However, along with the natural reducing trend of erosion in the Jamuna River since the 1990s, riverbank protection works might have contributed a bit to reducing the riverbank erosion rate.

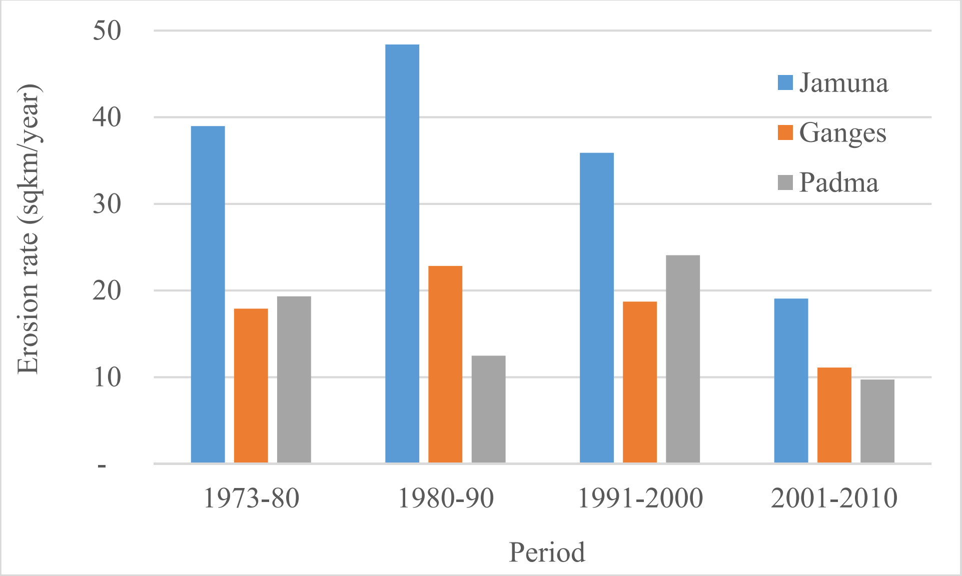


Figure 3.8: Rate of erosion during different periods

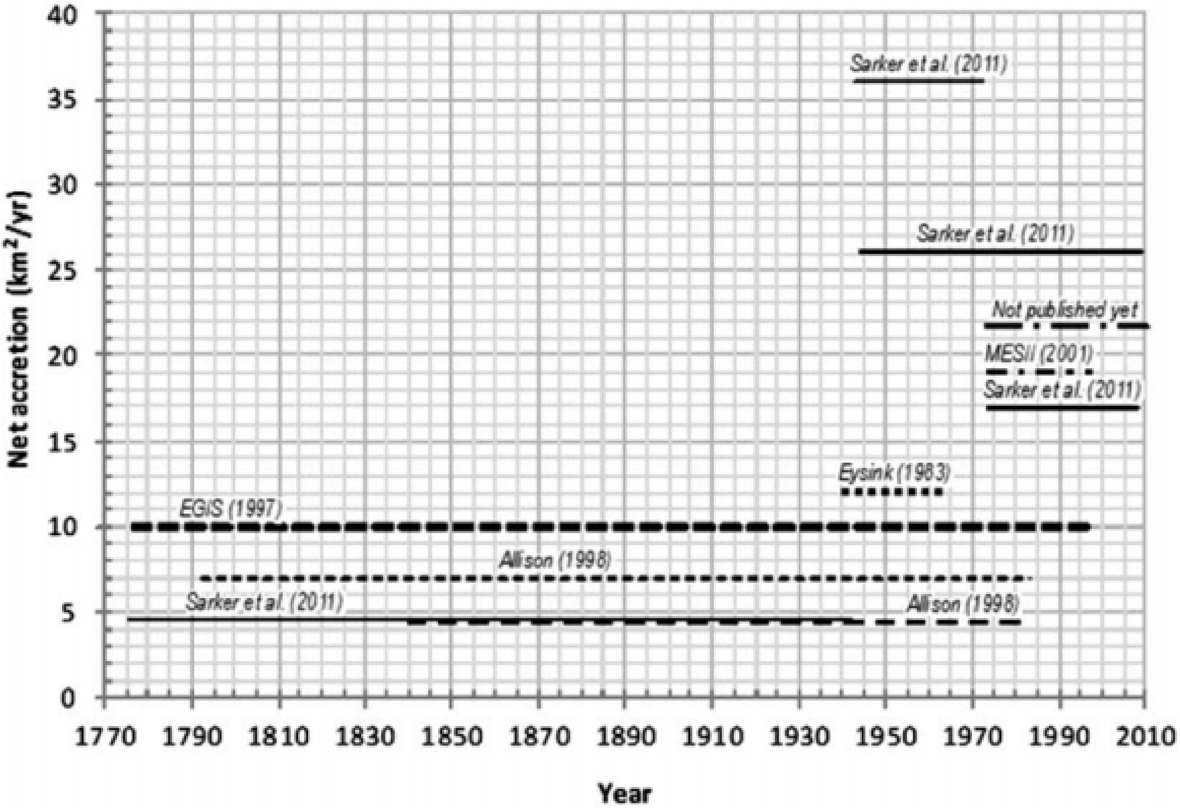
Cohesive sediment along the Ganges River banks (CEGIS, 2003), is mainly responsible to cause a balance erosion (280 sqkm) –accretion (260 sqkm) during 1973-2009. Relatively finer bed materials (0.15 mm) and lower river slope (6 cm/km) of the Ganegs River has made the river to be less dynamic in comparison to the Jamuna River, which has bed materials of 0.2 mm with a 7.5 cm/km river slope. The erosion rate was higher immediately after the construction of the Farakka Barrage from the 1960s till 1975 in India that could trap mainly the coarse material initially which mainly causes a river morphologically dynamic. Hence, the erosion rate during the 1980s was at a higher rate, nearly 23 sqkm per year. Erosion in this meandering river was mainly observed in the meandering bends.

The left bank materials of the Padma River are less erodible than that of the right bank (CEGIS, 2004). During 1973-2009, the erosion (400 sqkm) was about five-fold more than the accretion (84 sqkm). Riverbank erosion processes in the Padma River are mainly dominated by a few large bends with a life span of one decade to three decades. Maunsell/AECOM, (2010) has observed a cyclic process of bend development for the last five decades for the Char Janajat bend (Maunsell/AECOM, 2010), right bank of the Padma, and the off-take of the Arial Khan River.

The Upper Meghna River has a more stable planform than those of the other three main rivers of Bangladesh, as it is characterized as an inert river that has more carrying capacity than it has been carrying. Being an under-fit river, accretion is the dominating process for adjusting to the new hydro-morphology.

3.7.2 Process in the Coastal Areas

An estimation of the century- to decade-scale erosion–accretion was conducted based on historical maps (Akter et. al., 2016) and available information in the literature by Allison (1998), Environmental and Geographic Information Services (EGIS, 1997), Eysink (1983), the Meghna Estuary Study (MES II, 2001), and Sarker et al. (2011), as shown in Figure 3.9. Accretion is the dominating process in the coastal region of Bangladesh, although it varies significantly based on the fluvial inputs and tidal ranges (Figure 3.9). Hence it is apparent that decade scale accretion rates vary from 19 to 36 km^2/year (considering MESII, 2001 and Sarker et. al. 2011), whereas that at century-scale varies from 4.4 to 9.9 km^2/year (considering Eysink, 1983; EGIS, 1997; Alison, 1998; and Sarker et.al. 2011). The land accretion rate has likely been accelerated by significant human interventions in the coastal area like cross-dams.



Source: Akter et al. 2016

Figure 3.9: Net accretion rates of the Lower Meghna area by different studies

The most land accretion in the Meghna estuary was occurred in Noakhali district (Sarker et al., 2011; and Rahman, Dragoni, and El-Masri, 2011), which is the left bank and sea exposed district and almost the eastern boundary of the delta. They also mentioned that the tidal circulation process in this area is the main driving force contributing to the net land formation. Akter et al (2016); and Rahman, Dragoni, and El-Masri (2011) explained that the dominating erosion process in the coast of the Sundarbans is mainly due to a lack of sediment supply from upstream and subsidence, along with SLR. Based on satellite image analyses of 1973 and 2010, Akter et al (2016) show that net accretion occurred in the Hoogly River estuary and the Meghna Estuary. Although Hoogly River had some fluvial input through diverting Ganges water by operating the Farakka Barrage since the mid-1970s, the presently active Meghna estuary has natural fluvial input. Hence, the Meghna estuary is fluvial flow and sediment-dominated, whereas the western part of the basin in Bangladesh and India, including the Sundarbans, is tide and wave-dominated. Figure 3.9 reveals that the total net accretion in the Meghna estuary area is about 790 km^2, and hence a yearly net accretion is calculated to be 21 km^2 in the Meghna estuary.

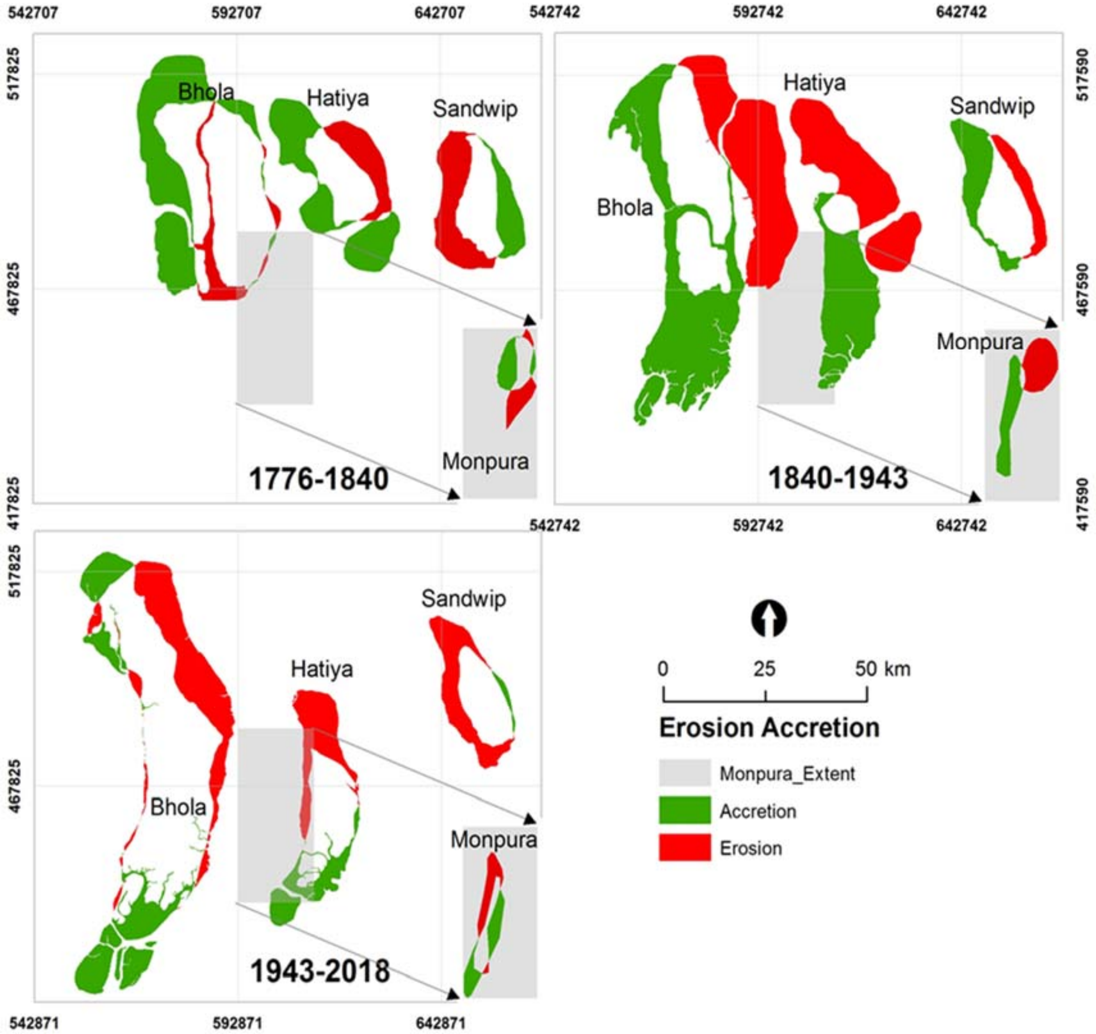
But, in centennial-scale changes, the Lower Ganges avulsed from its old course and joined with Meghna at Chandpur. As a result, huge land accretion occurred in the Meghna Estuary area, By 1943, Bhola island elongated and the Shahbazpur Channel widened. Meghna (distributary) at flowing along both sides of the Sandwip island was abandoned. The mainland was prograded southward. In decade-scale changes, three major islands were bounded by four distributaries Tetulia, Shahbazpur, Hatiya, and Sandwip in 1943. Huge sediment generated from the 1950 Assam earthquake caused the abandonment Lower Meghna Distributary. Abandonment of the Lower Meghna and decline of the Tetulia channel increased the flow to the Shahbazpur Channel and declined Bhola island elongated and Shahbazpur Channel growing bigger (Sarker el at, 2021). In the last 242 years, from 1973 to 2018, Bhola moved 50 kilometers to the south, Hatiya 30 kilometers, and Sandwip a few kilometers.

Changes in net accretion are quite unpredictable. Sarker et al, (2021) was able to establish the reasons (drivers) for such irregular behaviour in Sarker and Thorne (2009) and Sarker et al (2011). This experience was quite beneficial in identifying the centennial-scale drivers. The rate of net accretion was tremendous at both the centennial and decade scales, with exogenous variables such as earthquakes, new-tectonics, and delta building processes playing major roles. It may last several decades if there is no new silt from upstream. Furthermore, It might also result in negative accretion.

3.7.3 Dynamics in the Islands in the Meghna Estuary

Based on Sarker et al, 2021, described the erosion accretion process in two scales: centennial (Figure 3.10) and decade (Figure 3.11) scales. On a century-scale, between 1776 and 1840, net accretion was extraordinarily significant, totalling 950 sqkm in 64 years, owing mostly to the abandonment of the Ganges' lower reach, which flowed along the west slope of Bhola island. Increased fluvial input expanded the river in the Lower Meghna. The northeast flank of Hatiya island and the west flank of Sandwip were both heavily eroded. Between 1840 and 1943, shore erosion along the northeast edge of Bhola, Hatiya, and Sandip islands was quite high. Erosion was the most prevalent morphological process across the estuary.

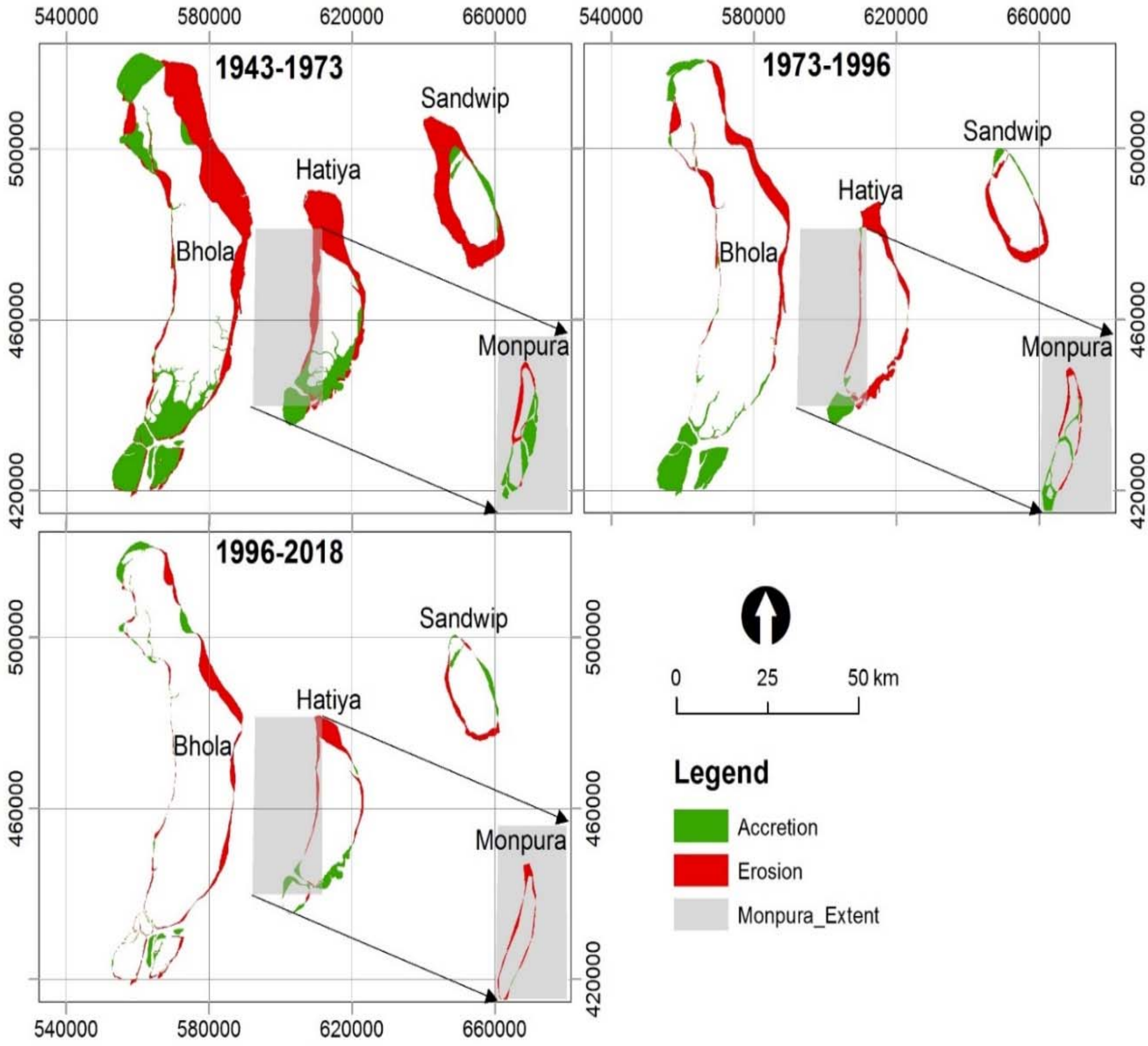
In the estuary, dramatic occurrences occurred. The Assam earthquake of 1950 produced many billion cubic meters of sediment which was carried to the estuary, causing a net accretion of 1700 sqkm. These three islands (Bhola, Hatiya, and Sandip), on the other hand, have seen net erosion.



Source: Sarker et al. 2021

Figure 3.10: Centennial scale erosion/accretion of the islands

Figure 3.11 shows the changes in decade scale based on available data. During the period 1943-1973, when the Meghna Estuary got massive net accretion, Bhola gained 50 Sqkm, whereas Hatiya and Sandwip lost 50 and 135 sqkm respectively. A significant volume of material from the north drove the islands southward, prograding the coastline and connecting to the mainland. In return, the delta prograded many kilometers towards the Bay of Bengal. Islands were eroded mostly when main distributaries flowed along the west or east margins of the islands. The southernmost points of the Bhola and Hatiya islands moved several kilometers closer to the bay. When huge distributary channels flowed down the east and/or west sides of the islands, significant shoreline erosion occurred.



Source: Sarker et al. 2021

Figure 3.11: Decade scale erosion/accretion of the islands

3.7.4 Processes as a Response to the Key Drivers

This research examined the drivers of previous events and assessed the role of the events and the system's responses to these events to improve the capacity to anticipate the response of the system. The following centennial-scale events have been identified: net accretion of 950 sqkm from 1776 to 1840 due to a large amount of sediment entering the Meghna Estuary possibly due to the avulsion of the Brahmaputra River; net accretion of 1700 sqkm from 1950 to 2020 due to landslides in the Himalayas caused by the 1950 Assam earthquake; and changes in size, shape, and location of the islands from 1840 to 2020, the main driver of which was the tide coming through the Oceanic Trench (along Hiron point).

Analysis of occurrences from 1950 to 2020 provided a better understanding of the decadal-scale events that occurred during this period. Between 1950 and 1973, there was a net accretion of 1200 sqkm, with significant fine sediment intake in the Meghna Estuary as the major cause. Between 1984 and 1996, the estuary had net accretion of 360 sqkm, which was mostly driven by a sediment slug (sediment wave). The estuary saw substantially reduced net accretion over the decades 1973 to 1984 and 1996 to 2020, and this trend may continue in the future provided the system is not disrupted.

From sandbars to mature mangrove forests or settlements, an island takes 12 to 22 years to form, making it a decade-scale morphological process (Sarker et al, 20011). In regions affected by the fluvio-marine process, island development takes less time, whereas, in areas dominated by the marine process, it takes more time.

The age of the chars/islands was used to determine their stability. Islands in the marine system are more stable than islands in the fluviomarine system, according to research done by Sarker et al 2021. Within the fluvio-marine system, the islands bordered by distributaries have a highly dynamic nature. The fluvio-marine system seems to have more morphological changes than the marine system, such as char formation, migration, and erosion/accretion.

3.8 Salinity Intrusion

Due to tidal effects, saline water goes upstream as far as 200 km due to its flat terrain. In addition, tidal amplitude controls landward intrusion, unless otherwise the area is dissected by coastal polder or flood embankment. Freshwater flow from upstream, along with tides and its circulation process primarily controls the salinity level in the coastal region, but shrimp cultivation may create an artificial saline zone. Hence, the south-central region of Bangladesh, where fresh flow comes through the Arial Khan and distributaries of the Lower Meghna River both in the dry and flood periods. Hence the salinity levels in the Baleshwar, Bishkhali, Burishwar-Payra, and Tentulia Rivers are much less than 5 ppt.

On the other hand in the case of the southwest region of Bangladesh, where Gorai is the only source of freshwater flow, the salinity scenario is different. Dry seasonal flow in the Gorai reduced significantly which was a tremendous effect on the salinity level in that region. Figure 3.12 shows the direct relationship between the Gorai River flow and salinity in the Rupsha River in Khulna. The figure exhibits that salinity level increases considerably when freshwater flow reduces to almost zero. In the southwest region, the maximum salinity was recorded as 28.2 ppt at Kaikhali union of Shatkhira district. However, in the eastern boundary of the delta, the salinity level is recorded more than 20 ppt where no freshwater flow exist.

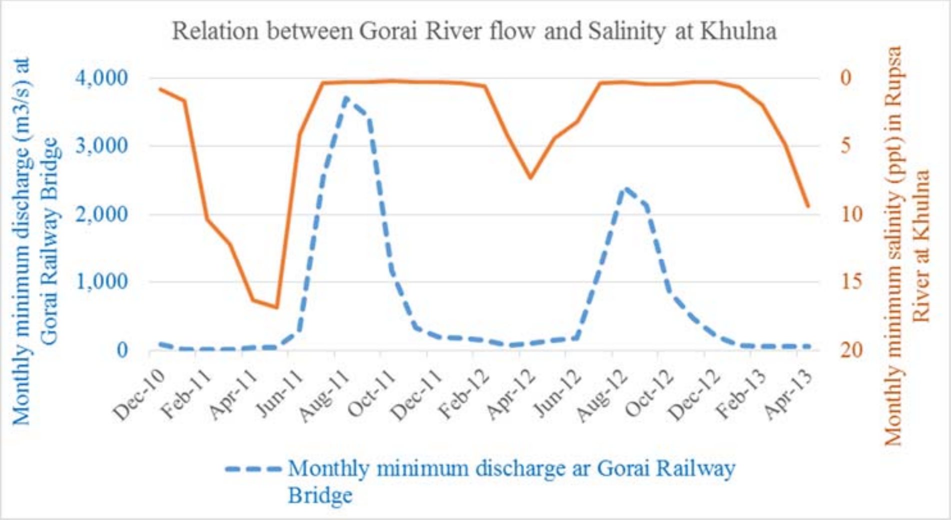


Figure 3.12: Relationship between the Gorai River flow and salinity in the Rupsha River in Khulna

3.9 Human Intervention

Records of small-scale embankments construction are found in the Statistical Account of Bengal published in 1877, to produce more food from floodplains and tidal plains and to make people safer. Although those interventions in this coastal region were not harmful to the natural system but were not enough to protect coastal lives and livelihoods from tidal flood and salinity intrusion. However, following the devastating flood in 1950 in this region, 139 polders were constructed during the 1960s to 1970s. Those polders support 8 million people in 1.2 million hectares of the coastal region in 2008 (BBS, 2010).

However, in the last 20th century, largescale interventions in the river systems of the southwest region of Bangladesh (Table 3.1) were mainly to improve communication networks, increase agricultural production, and in final to enhance safety in the coastal environment. In the first half of the 20^{th} century, during the British regime, several artificial connectivities were made to maintain or improve navigation in the delta. All these connections modified the hydrological regime significantly. Furthermore, unplanned railways and highways construction over the floodplain has restricted the free flow of floods over the terrain.

Table 3.1: Major connectivity made during the 20^{th} century

Connectivity name	Purpose and consequence	Made in
Halifax cut	For connecting the Madhumati River with the Nabaganga River to shorten the distance from Dhaka to Khulna. A significant amount of flow of the Madhumati River started to be diverted through the Nabaganga River.	1910
23-km Madaripur Beel Route	For connecting the Arial Khan River with the Madhumati River. A part of the Arial Khan River flowed into the Madhumati River.	1910 – 1912
Gabkhan Channel	For reducing the navigation distance by around 118 km. The Sandhya River of the Pirojpur district and the Sugandha River of the Jhalakati district are connected.	1918
Mongla-Ghashiakhali Canal	For reducing the navigation distance	1974

In the second half of the 20th century, several flood embankments and polders were constructed in the floodplain and tidal plains for the aim of better water management for flood protection and more food production. Although people initially benefited, by the early 1980s the secondary effects of polderization in terms of sediment deposition on the tidal plain began to be serious. However, the Farakka Barrage in India diverts water from the Ganges for the sustenance of the Kolkata port, which has serious consequences on the hydrology of southwest Bangladesh. Many rivers and tidal channels died within a few years to a few decades. All these human interventions have created drainage congestion and sediment erosion inside the polder, and over sedimentation in the river channels causing high tidal amplification and deterioration of navigability.

3.10 Climate Change

3.10.1 Temperature, Rainfall, and Discharge

Due to its geographical location along with huge water and sediment flow, Bangladesh is likely to be one of the most vulnerable countries to the effects and severity of climate change. Single or combined alteration of the factors in the river catchment would have an impact on the river and estuary. During the morphological adjustment process, the river and estuary would be more dynamic. However, Akter et al 2016 gave emphasized the understanding of the responses of rivers and estuaries of Bangladesh to climate change for fixing a strategy for adaptation to climate change.

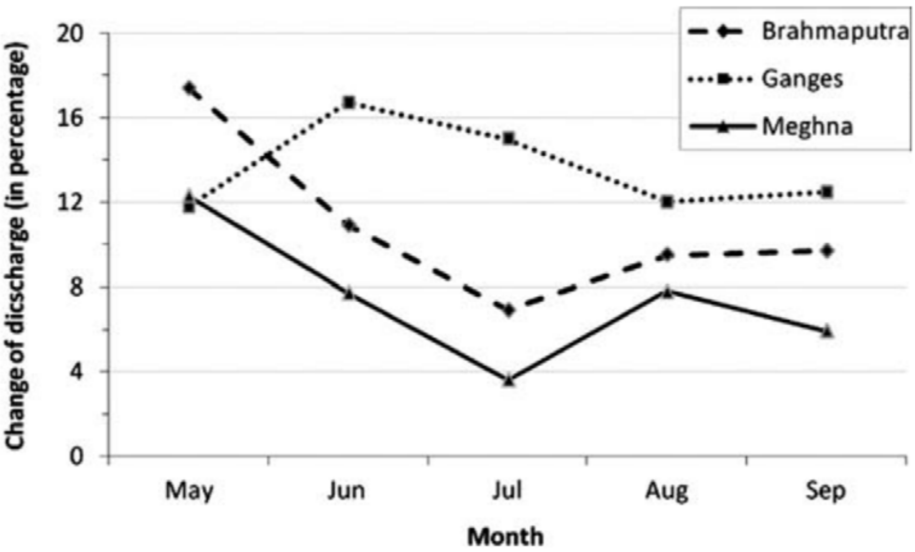


Figure 3.13: Estimated average changes of percentage in discharge in monsoon

The temperature and rainfall data from the 1960s to 1993 in Bangladesh do not show any significant changes (Haque and Quadir, 1997). Although Fischer et.al. 2016 mentioned the increase in precipitation in the Brahmaputra-Jamuna river (Bangladesh part, ranges from 13 % (Masood et al. 2015) to 39 % (Darby et. al. 2015), based on the analysis of data from 1980 - 2000. But according to the IPCC's 1990 business-as-usual scenario, river discharge will increase if rainfall increases (Tegart, Sheldon, and Griffiths, 1990). Mirza (2005) found that for a 2^0C increase in temperature, the maximum change in rainfall could be 13% and 10.2% in the Ganges Basin and the Brahmaputra Basin, respectively, causing increases in the mean annual discharge by 21.1% and 6.4%. Recently, Yu et al. (2010) projected that the increase in temperature of 0.75^0C, 1.55^0C, and 2.4^0C would cause a median precipitation increase of 1%, 4%, and 6% in 2030, 2050, and 2080 respectively; and the change of monsoon discharge in 2050 are presented in Figure 3.13. They projected that increase of the average discharge in August and September, would be about 10%, 12%, and 7% in the Brahmaputra, Ganges, and Meghna, respectively.

3.10.2 Sea Level Rise and Inundation

Climate change associated with increased rainfall would undoubtedly increase the flood discharge in the river system causing corresponding inundation in the floodplain and tidal plain. In addition, SLR would increase the spatial and temporal extent of tidal flooding. So, both the increased rainfall and SLR would cause an increase in inundated area and depth. More than 50% of Bangladesh delta is less than 5 m above mean sea level, based on the available digital elevation model (Akter et al 2016). So, every single centimeter of SLR will have consequences in the coastal plain of Bangladesh. Different studies show a range of inundation results due to SLR.

Table 3.2: A range of inundation areas by different studies

SLR	Inundation area	Authors
1 m	17 % of Bangladesh	Choudhury, Haque, and Quadir, 1997
1 m	21% of Bangladesh	IPCC, 2001
88 cm	11% (4,107 sqkm) of the coastal zone (about 3% of the total area of Bangladesh)	WARPO, 2005
62 cm	16% additional inundation (5500 sqkm) in the coastal region of Bangladesh	IWM and CEGIS, 2007

Source: Akter et al, 2016

3.11 Summary

The Ganges-Brahmaputra-Meghna system's current dynamics are described in this chapter. When it comes to the response of the delta to different natural and human interventions, there are considerable variations in opinion and diverse findings in the literature. The behaviour of the delta and estuary system has been studied at several time scales, and the history of the estuary has been reconstructed for the last 250 years to identify key events and drivers at various scales. The rate of net accretion was enormous on both a centennial and decade scale. The 1950 Assam earthquake, neotectonics, and delta-building processes were all-important external influences.

There is linkage between external influences and morphological processes on the islands. Any large-scale human interventions or disruptions have an impact on the entire estuary. Aside from variations in fluvial input, tidal features have a significant impact on the shape and migration of islands. In the last 242 years, from 1776 to 2018, Bhola's southern point migrated 50 kilometers, Hatiya 30 kilometers, and Sandwip a few kilometers.

Erosion and accretion processes were found to be highly erratic on both a centennial and decadal-scale to the identified events, as well as varied on both scales. The knowledge and information collected in this chapter aid in the development of the Process-Response Model.

Chapter 4

Climate Change Scenarios for the Ganges-Brahmaputra-Meghna Delta

Climate change-related Global and regional projections under different research have been briefly discussed in this chapter. Based on projections made for Bangladesh relating to flow and sediment discharge, subsidence, and sea-level rise, four scenarios are developed for future simulations.

4.1. Introduction

Increased temperature (global warming) is the main factor for initiating all the factors, like- snow-melting, increased evaporation, change in rainfall and river discharge, and sea-level rise (SLR). Change in temperature of the earth is not a new phenomenon, but a continuous process since its creation. Global mean sea level exceeded 5 m above present during the pre-industrial period when the global temperature was 2^0C higher (IPCC, 2013). The universe has its cycle of a low stand (ice age) and high stand (warm). But alarming thing is that whether the earth and its environment are ready to cope up with the anthropogenic high rate of temperature change. Due to the low pace of the environment with increased temperature, the world is facing several natural disasters.

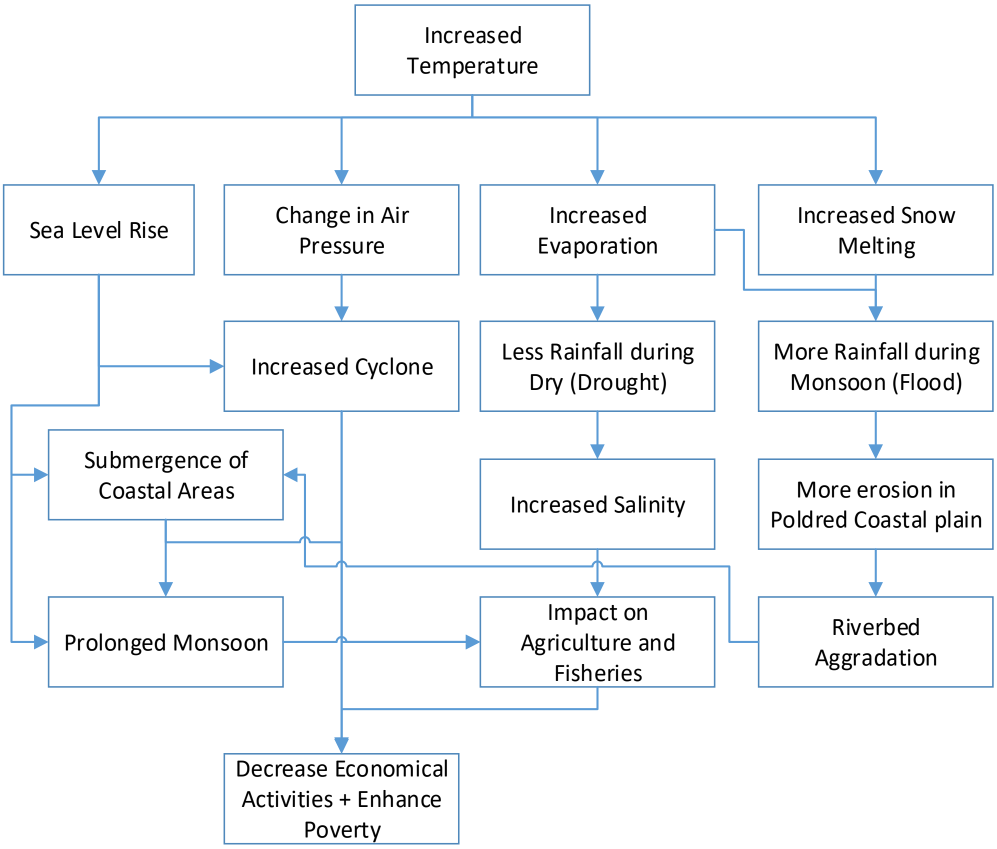


Figure 4.1: Climate change and man-made Impacts on the drainage system of Bangladesh

Bangladesh has been declared one of the most vulnerable countries to climate change in the world (IWM, 2008; IWM and CEGIS, 2007; Mirza and Ahmed, 2005; Brammer, 2014; and Akter et al 2016; Choudhury et al, 1997). As a series of consequences of climate change, Bangladesh is facing increasing cyclones, tidal surges, erosion, inundation, salinity intrusion, and many more. These consequences have a severe direct impact on a country’s socio-economic activities. Figure 4.1 shows the possible consequences of increased temperature on Bangladesh's socio-economy.

4.2. Climate Change Scenarios

Based on IPCC (2013), in the Socio-Economic Driven SRES Scenarios (Special Report on Emission Scenarios), the climate change projections were undertaken as part of Coupled Model Intercomparison Project Phase 3 (CMIP3) and discussed in The Fourth Assessment Report (AR4) based on the SRES A2, A1B, and B1 scenarios. On the other hand, the Representative Concentration Pathway (RCP) Scenarios, are new scenarios that specify concentrations and corresponding emissions but are not directly based on socio-economic storylines like the SRES scenarios. The four RCP scenarios used in Coupled Model Intercomparison Project Phase 5 (CMIP5) lead to radiative forcing values that span a range larger than that of the three SRES scenarios used in CMIP3. RCP4.5 is close to SRES B1, RCP6 is close to SRES A1B (more after 2100 than during the 21st century) and RCP8.5 is somewhat higher than A2 in 2100 and close to the SRES A1FI scenario.

A1 scenarios: very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. A1FI (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel)

A2 scenarios: very heterogeneous world. Economic development is primarily regionally oriented and per capita, economic growth and technological change are more fragmented and slower than in other storylines.

B1 scenarios: a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

B2 scenarios: the emphasis is on local solutions to economic, social, and environmental sustainability.

4.3. Global and Regional Climate Change Projections

The Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) projected global average surface warming, global SLR, and South-

Asian precipitation under different scenarios, which are shown in Table 4. 1 and Table 4. 2. Under the A1F1 scenario, AR4 (IPCC, 2007) projected that the highest amount of global average SLR during the 21st century would be in the range of 0.26 m to 0.59 m, whereas the global temperature would increase in the range of 2.4-6.4ºC. For the same scenario, the projected increase in the monsoon seasonal rainfall is 26% for South-Asia (IPCC, 2007). However, Mirza and Ahmed (2005) indicated an increase in the vapour concentration and rainfall in South Asia within the next 100 years. They mentioned that the average change in precipitation would be between 5 and 20%.

Table 4.1: Projected global average surface warming and SLR by 2100 under different scenarios

Item	**Scenarios**					
	B1	A1T	B2	A1B	A2	A1F1
Temperature (ºC)	1.1 – 2.9	1.4 – 3.8	1.4 – 3.8	1.7 – 4.4	2.0 – 5.4	2.4 – 6.4
SLR (m)	0.18 – 0.38	0.20 – 0.45	0.20 – 0.43	0.21 – 0.48	0.23 – 0.51	0.26 – 0.59

Source: IPCC, 2007

Table 4.2: Projected precipitation change in South Asia during the 21st century

Months	**2010 – 2039**		**2040 – 2069**		**2070 - 2099**	
	Scenarios					
	A1FI	B1	A1Fl	B1	A1Fl	B1
DJF	-3	4	0	0	-16	-6
MAM	7	8	26	24	31	20
JJA	5	7	13	11	26	15
SON	1	3	8	6	26	10

Source: IPCC, 2007

The Fifth Assessment Report (AR5) of IPCC has projected a 4.49^{0}C increase of global mean temperature under the A1FI scenario. Projections of SLR as mentioned in AR5 are also larger than in AR4, mainly due to the inclusion of land-ice contribution in their improved modelling works (IPCC, 2013). For the RCP8.5 scenario, the global mean sea level is expected to rise in the range of 0.53 to 0.98 m. According to IPCC (2013), global mean surface temperature change based on SRES scenarios and global mean SLR based on RCP scenarios is shown in Tables 4. 3 and 4.4. For South Asia, a similar projection for summer precipitation that is the dominated annual rainfall is shown in Table 4.5. The rainfall in Bangladesh would increase strongly (IPCC, 2013).

Table 4.3: Global mean surface temperature change (°C) in 2100 relative to 1990

Scenarios	A1T	A1Fl	A2	B1	B2	IS92a	A1B
Global temperature change (°C)	2.54	4.49	3.79	1.98	2.69	2.38	2.95

A1FI (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel)

Table 4.4: Global mean sea level rise (m) from 2100 to 1986-2005

Scenarios	SRES A1B	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Global mean sea level rise (m)	0.60	0.44	0.53	0.55	0.74
Ranges (m)	0.42-0.80	0.28 - 0.61	0.36-0.71	0.38-0.73	0.53-0.98

Table 4.5: Temperature and precipitation projections for 2100 to 1986-2005 by the CMIP5 global models based on the RCP4.5 scenario

Parameter	Months	min	Percentile			max
			25%	50%	75%	
Temperature (^{0}C)	Dec-Jan-Feb	1.4	2.0	2.3	3.0	3.7
	Jun-Jul-Aug	0.7	1.4	1.7	2.2	3.3
	Annual	1.3	1.7	2.1	2.7	3.5
Precipitation (%)	Winter (Oct-Mar)	-14	0	8	14	28
	Summer (Apr-Sep)	-7	8	10	13	37
	Annual	-3	6	10	12	27

4.4. Projections for Bangladesh

4.4.1. Precipitation and Water Discharge

Due to geographical location, very flat and low-lying terrain, high population density, poor income, along illiteracy, Bangladesh has already been declared one of the most vulnerable countries to climate change impact. Although trend analysis with short period temperature and rainfall data is not representative due to its different time scale variation; Choudhury, Haque, and Quadir (1997) did not find significant changes in the temperature and rainfall data from the 1960s to 1993 in Bangladesh (Akter et al 2016). Still, rainfall would increase with an increase of temperature, under the IPCC's 1990 business-as-usual scenario (Tegart, Sheldon, and Griffiths, 1990).

Based on an empirical model, the probable maximum change in precipitation in the Ganges Basin and the Brahmaputra Basin might be 13% and 10.2%, respectively, for a temperature increase of 2^0C (Mirza, 2005). These increases of precipitation in the Ganges Basin and the Brahmaputra Basin would cause increases in the mean annual discharge by 21.1% and 6.4%, respectively. Later, IWM (2008) found that a 13% increase in precipitation over the Ganges basin would increase 22% peak discharge at Hardinge Bridge of the Ganges River. Nevertheless, in all cases, any increase in temperature or rainfall in the catchment will increase the discharge downstream.

Recently, Yu et al. (2010) projected the effects of climate change on Bangladesh for three periods—up to 2030, 2050, and 2080. They projected increases in temperature as 0.75^0C, 1.55^0C, and 2.4^0C with a median precipitation increase of 1%, 4%, and 6%, respectively for those three time periods. Consequently, the discharge during monsoon would increase by 2050 (Figure 4.2), but the monthly increase rates would be different by 2050 based on five generator condition monitors and two special reports on emissions scenarios model experiments (Yu et al., 2010). Although, the rates would vary from river to river. The average discharge increment in two monsoon months, i.e. August and September, would be about 10%, 12%, and 7% in the Brahmaputra, Ganges, and Meghna rivers, respectively.

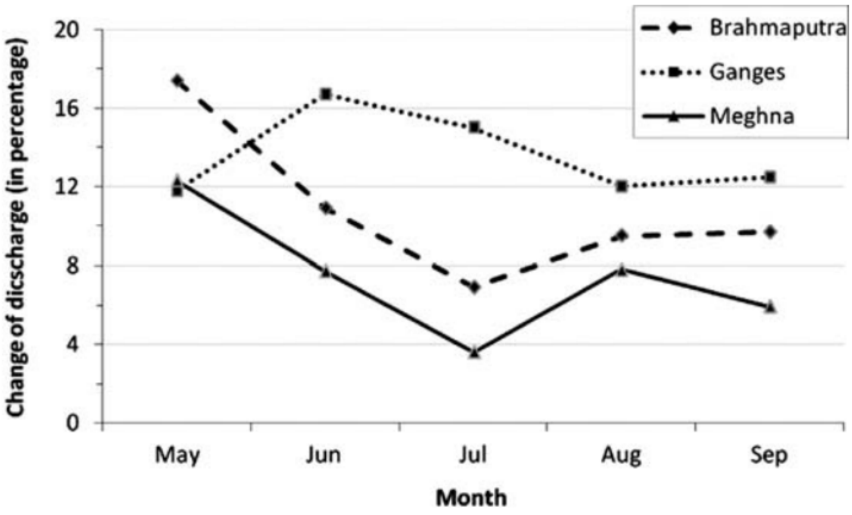
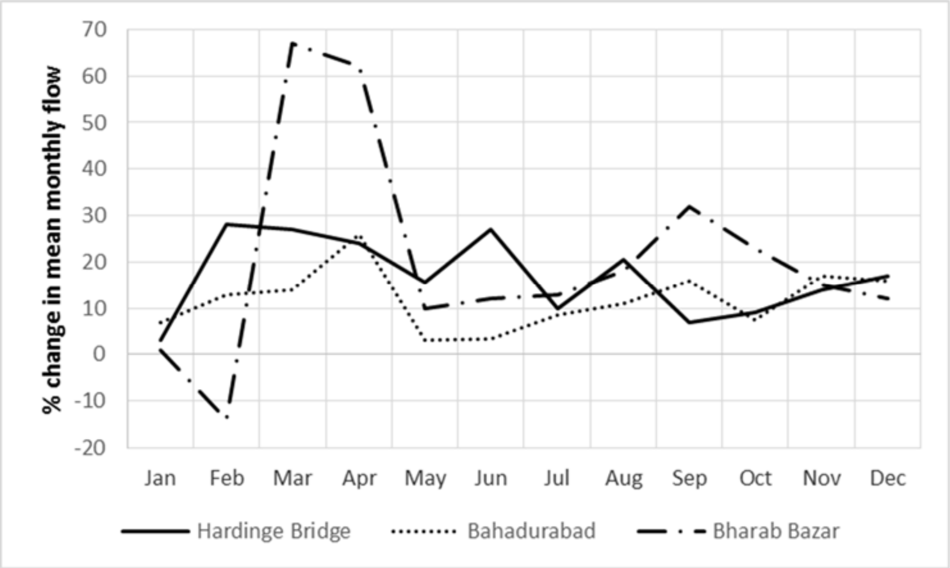


Figure 4.2: Estimated average changes of percentage in discharge by 2050.

However, Hossain, M. M., Zaman, A. M., and Fulco Ludwig (2015) assessed climate change impact on discharge from projected daily discharge at Harding Bridge, Bahadurabad, and Bhairab Bazar based on the RCP8.5 scenario. This scenario is considered to be the worst-case scenario, where emissions will increase rapidly during the early and mid-parts of the 21st century. They showed that monsoon water discharge at Hardinge Bridge, Bahadurabad, and Bhairab Bazar will increase by 7-27%, 4-13%, and 12-32% in the Ganges, Brahmaputra, and Meghna Rivers respectively (Figure 4.3).



Data source: Hossain et al., 2015

Figure 4.3: Monthly flow change at Hardinge Bridge, Bahadurabad, and Bhairab Bazar by 2100 under the RCP8.5 scenario.

4.4.2. Sea Level Rise in the Bay of Bengal

SLR is another climate change-induced factor that has a direct relation with the hydrological regime of Bangladesh. Intensified monsoon rainfall would increase the flood discharge in the river system. In addition, SLR would increase the extent of tidal flooding after its propagation towards the land. Both of these climate change-induced factors would ultimately increase flooded area and inundation depth. The digital elevation data of Bangladesh indicates that about 50% of the area is less than 5 m above mean sea level. Therefore, a 1-cm SLR would even have negative socioeconomic consequences for the country.

Different studies on inundation have found varying results. An SLR of 1 m would cause inundation of 17% of the total area of Bangladesh (Choudhury, Haque, and Quadir, 1997). In the same way, IPCC (2001) predicted about 21% of total land inundation because of an SLR of 1 m. Nevertheless, about 11% (4,107 sqkm) of the coastal zone (about 3% of the total area of Bangladesh) could be more heavily inundated, at an 88-cm SLR, in 2100 (WARPO, 2005). A 62-cm SLR, along with increased rainfall in the next 100 years, could cause 16% additional inundation (5500 sqkm) in the coastal region of Bangladesh (IWM and CEGIS, 2007), based on a numerical simulation considering no changes in river bathymetry, floodplain, and tidal plain topography. With the same physical setting, Yu et al. (2010) projected additional flooding because of SLR and increased discharge in the rivers using numerical modelling. They mentioned that the flooded area in the Ganges and Jamuna floodplains would increase at varying rates in different months for different regions. Flooding would increase about 10% by August 2050 in the Ganges and Jamuna floodplains.

However, a different approach for predicting flooding because of SLR and increase in precipitation because of climate change was adopted by Brammer (2004). He considered the concurrent rising of estuarine plains with the rising of sea level; therefore, no additional flooding would be expected in those areas. Similar assumptions were also made for the natural levees along the tidal and estuarine rivers. Therefore, the inland flood basins in the south-central region, where sediment can barely reach, would be the most vulnerable to flooding. Brammer (2004) indicated the flood-vulnerable areas qualitatively based on agro-ecological regions. He also indicated that after the next 50 years, it is likely that flooding will increase in the Middle Meghna floodplain, the middle section of the Low Ganges River floodplain, and Old Meghna estuarine floodplain, and low-lying Sylhet Basin because of impeded drainage.

4.4.3. Sediment Discharge

Akter et. al., (2016) mentioned that any hydro-climatological change in the river catchment will change the flow and sediment regime of the river and the estuary system. During the time lag of the fluvial process and morphological form adjustments, the system would become more dynamic and unpredictable. With higher flow and sediment, the river and its estuary would be more dynamic, which would result in some net accretions. On the contrary, if the sediment input is reduced in the system, net erosion will take place. Therefore, the expediting rate of climate change is very likely to cause several changes in the physical processes.

Furthermore, Brammer (2014) mentioned that the growth rate of the Meghna estuary was 19.6 sqkm/year between 1984 and 2007. This net annual land gain might have been observed after combating the land loss generated by SLR. But this growth rate would be impacted by dam construction and sediment management in the upstream catchment area.

Fischer et. al., (2017) has considered a 40% annual increase in sediment load for the Brahmaputra River during the high-flow (May-Oct) season, as 90% of the annual load is transported during the monsoon flood. Derby et al (2015) considered an increase of 52-60% in total sediment load for the end of the century in comparison to the load during 1981-2000. Although construction of reservoir and dam would decrease sediment.

Rahman et al. (2011) have reported that 30% flow of the Ganges was diverted from the main channel after the Farakka Barrage construction in 1975. This large-scale reservoir trapping would probably be the cause of huge erosion in the Sundarban Mangrove forest (Fischer et. al., 2017). Similar to the Brahmaputra, about 80% of the Ganges discharge and 95% of its sediment load are delivered to the margin in only 4 months, making the system extremely sensitive to this seasonal forcing (Goodbred, S., 2003).

4.4.4. Subsidence

Along with rising sea levels, subsidence is another alarming factor for Bangladesh, especially for coastal people. There is much contradictory information regarding the subsidence rate in Bangladesh. Syvitski et al (2009) mentioned Bangladesh as one of the 33- ‘sinking deltas’, with a rate of 18 mm/year. Sarker et al. (2012) showed that the long-term subsidence rate in the coastal floodplain should not exceed 1-2.5 mm/year, based on plinth level measurement of some longstanding structures. Hanebuth et al., (2013) suggested a rate of 5.2±1.1 mm/year for the eastern part of Sundarbans; whereas Stanley and Hait, (2000) suggested 5 mm/year for the south of the Indian Sundarbans. Based on the available studies, Brammer, H (2014) recommended a subsidence rate of 2 mm/year for most of the region of Bangladesh and 6 mm/year along the coast.

4.5. Summary

Based on the literature review and data availability, scenarios have been formulated for future modelling simulations considering increased water and sediment discharge upstream, increased SLR downstream, and subsidence. These simulations will help to understand the response of the delta and main river system as a consequence of climate change-induced increased water and sediment discharge and SLR.

Chapter 5

Process-based1-D modelling of the long-term morphodynamic evolution of the Ganges-Brahmaputra-Meghna Rivers

The Ganges-Brahmaputra-Meghna (GBM) delta in Bangladesh covers an extensive and morphodynamically highly active area. Apart from seasonally and annually varying river flow the three major rivers supply vast amounts of sediment that partly settle in the delta and partly discharge into the ocean. This raises questions on morphodynamic equilibrium and associated adaptation time scales. In absence of long-term bathymetric datasets, morphodynamic modelling provides a useful tool to explore the GBM delta dynamics. A one-dimensional (1D) process-based morphodynamic model was used to analyze the long-term evolution of the Ganges-Brahmaputra-Meghna (GBM) rivers in Bangladesh, from Bahadurabad to the present delta mouth, the Meghna Estuary. A sensitivity analysis was carried out for assessing the effects of varying mean sea level (MSL), depth at the river mouth, river-bed slopes, bed roughness, and the shape of the river width. Though highly simplified and based on rough assumptions considering the initial bathymetry due to a lack of data, the 1D model reproduces water levels in promising agreement with scarce, measured water level data. Sensitivity simulations suggest that seasonal variation in the MSL has a strong impact on the hydrodynamic behaviour of the GBM system. The morphodynamic 1-D model shows that an equilibrium configuration occurs within a millennium scale, with bed aggradation in the downstream delta system. This may trigger a significant change in hydro-morphology, including river system avulsion.

5.1. Introduction

5.1.1 Modelling Geomorphology Towards Equilibrium

Rivers carry sediments into the ocean supply sediment from their catchment into the ocean (Owens, 2007). Under conditions of ample sediment supply, a portion part of these sediments will deposit in the estuarine plain, raising the local bathymetry and leading to progradation of the river delta (Sarker, et al. 2011). In most large-scale delta systems, data on channel geometry and bathymetry, or water and sediment fluxes throughout the delta distributary network are lacking. Measurements are typically made in the main tributary at its apex. How the dispersal of sediment downstream occurs remains largely unrecorded? Even less known is mostly unknown. The process of reworking sediment from offshore river plumes back into the estuarine plain, as well as and the associated long-term morphodynamic development, is even less well-known. Seasonally varying river flow and sediment supplies result in supply leading to seasonally varying morphodynamic development that is also seasonal. A fundamental question relates to whether estuaries may morphodynamically evolve towards equilibrium, and, if so, what time scales are associated with this equilibrium. This study aims to explore these dynamics for the Ganges-Brahmaputra-Meghna (GBM) Delta in Bangladesh through one-dimensional (1-D) modelling. Results may later be used for more computationally expensive two-dimensional (2-D) modelling.

The GBM delta is a good example of a huge system lacking data (Masood, et al. 2015). Data scarcity is one of the main drawbacks of working on long-term geomorphological processes for any delta system. Data on channel geometry and bathymetry, as well as water and sediment fluxes across the delta distributary network, is missing in many deltaic systems around the world. Even more datasets on the evolution of these factors over different time ranges are scarce (Akter, et al. 2021). Although modelling can reproduce the system under different prevailing processes quickly, it is a commonly held belief that these models also require more precise data for model setup, calibration, and validation.

However, exciting advancements in two-dimensional depth-averaged (2DH) numerical models of river morphodynamics have occurred in recent decades due to rapid developments in stable numerical techniques (Mosselman and Le, not even a complete momentary bathymetric data set has ever been recorded. Datasets of continuous river flow or water levels are present for a very limited number of stations. Measurements by specific organizations are available but are mostly not publicly accessible. Measurements of suspended sediment concentration (SSC) are even scarcer and typically cover only short periods. Hence it is difficult to understand the distributions and fate of river-borne sediments as well as to assess the system's reaction to future scenarios of possible river flow and sediment reduction, subsidence, and sea-level rise (SLR). Few studies are devoted to morphodynamics like delta shifting and river avulsion (Akter et al., 2016; Sarker et al., 2011; and Sarker, Akter, and Rahman, 2013). It is important to understand whether the Meghna estuary is aggrading, degrading, or tends to attain morphodynamic equilibrium in the coming decades since many people depend on its course for daily life.

River-bed slope, depth of the river at the river mouth, and mean sea level (MSL) are important parameters for understanding the long-term morphodynamic behaviour of the system. Modelling efforts would help to understand this behaviour and the impact of future scenarios including the impact of SLR. However, the required bathymetric data are local and scarce. There is no bathymetric data describing the entire system, let alone sequences of bathymetric development to validate a morphodynamic model. Still, numerical models with proven value by validated case studies may help to explore the long-term morphodynamic evolution of this ebb-dominated estuary. Here we provide results on the hydrodynamic and morphodynamic behaviour of a 1-D Meghna estuary model that is affected by both tidal and fluvial processes.

Numerical models help to create a unique virtual laboratory system with simple or multiple complex processes. Studies on the relevance of cohesive sediments in delta development (Edmonds and Slingerland, 2010) or the influence of waves on mouth bar growth (Nardin and Fagherazzi, 2012) are examples of a schematized approach. Edmonds and Slingerland (2010) have used a numerical flow and transport model, Delft3D, to find the role of sediment cohesion, i.e. sediment size and type of vegetation, in shaping the morphodynamics of deltas. Gelfenbaum et. al., (2009) used a process-based morphodynamic model for predicting sediment transport pathways and delta morphological responses response to changes in sediment supply in a more realistic context after the removal of two dams on the Elwha River in Washington State, USA. Elmilady et.al. (2019) and Ganju and Schoellhamer (2010) expertly replicated the observed event, because of the expulsion of two dams. Nardin and Fagherazzi (2012) explored the effects of waves on mouth bar growth with Delft3D. Elmilady et al. (2019) worked on some real data modelling in San Pablo Bay, California, the USA with Delft3D. They assessed the value of process-based morphodynamic modelling by hind-casting and forecasting 250 years of morphodynamic development. Model outcomes were evaluated against measured bathymetric developments, and the model could predict decadal timescale morphodynamic changes developments in San Francisco North Pablo Bay (California, USA) and forecasted climate change's prospective impact with significant skill. Guo et al, L. (2014) explored the fundamental effects of tidal asymmetries, river discharge, and river-tide interaction in governing residual sediment transport and associated long-term estuarine morphodynamics in the Yangtze estuary (China). Thus, numerical models aid in the creation of a one-of-a-kind virtual laboratory system with processes of varying complexity.

Akter et al, 2021 derived a sediment budget for the Ganges-Brahmaputra-Meghna (GBM) delta in Bangladesh based on a full morphodynamic approach with a 2D model covering an area of 300 km by 350 km. Although the 2D model results resembled the observed morphodynamic development of channel shoal patterns, computational efforts were considerable (more than a month for a simulation with 240 days data), not allowing for a closer analysis of system-wide equilibrium conditions and associated morphodynamics adaptation time scales under the combined river and tidal forcing, based on schematized modelling mimicking the GBM delta.

The purpose of this work is to develop a morphodynamic model to explore the first-order dynamics of GBM bathymetry. Research questions are related to the time scale of the morphodynamic evolution of the system, the possible existence of (dynamic) equilibrium, the impact of river supply pulses, and the impact of SLR along with subsidence. Model results and gained insight may eventually be used as input for a more detailed 2-D model. This research aims to explore these dynamics for a huge delta system through one-dimensional (1D) modelling. A sensitivity analysis was carried out for assessing the effects of varying mean sea level (MSL), depth at the river mouth, river-bed slopes, bed roughness, and the shape of the river width.

5.1.2. Ganges Brahmaputra Meghna Delta

The Ganges, the Brahmaputra, and the Meghna rivers are the three main river systems for the GBM delta. The Ganges (draining southern slope of the Himalayas) and the Brahmaputra (draining northern slope of the Himalayas) rivers merge at Baruria and flow together for 110 km as the Padma River until this meets the Upper Meghna River at Chandpur, as shown in Figure 5.1. Then finally, it meets the Bay of Bengal named the Lower Meghna River. Measurements at Hardinge Bridge, Bahadurabad, and Bhairab Bazar on the Ganges, Brahmaputra, and Meghna rivers respectively are important for modelling this delta system. The Ganges has had many human interventions in the upstream reach before it enters

Bangladesh (Muhammad, 2003), whereas the Brahmaputra has had less intervention. For this 1-D modelling work, we considered Brahmaputra-Padma-Lower Meghna river systems. We are often called the Brahmaputra Jamuna, as it is a hydrologically unique name of the Brahmaputra after it diverts the water to the Old Brahmaputra River upstream at Bahadurabad.

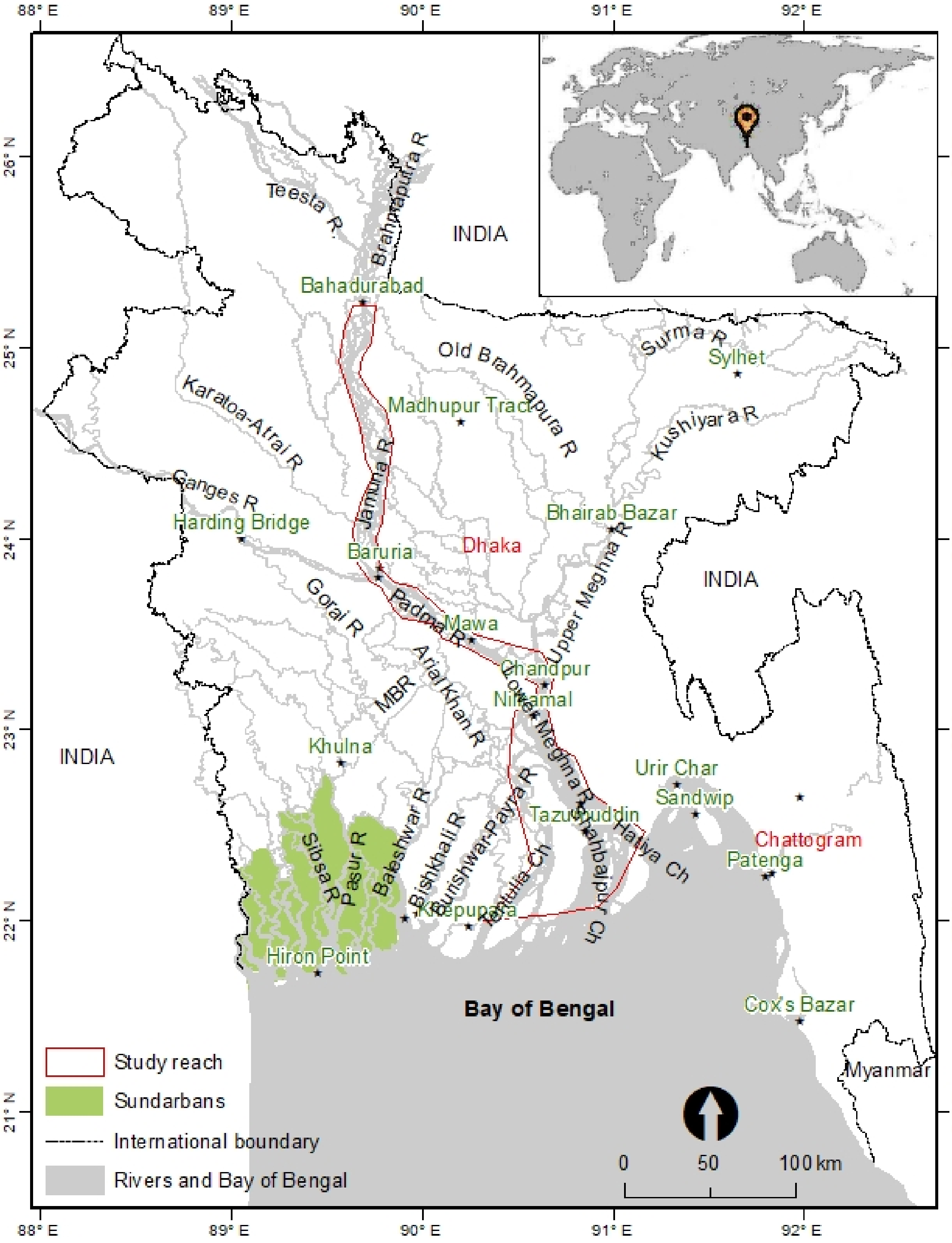


Figure 5.1: The Ganges, the Brahmaputra, and the Meghna rivers in Bangladesh

The annual average water discharge in the Brahmaputra (20,200 m^3/s) is almost double that of the Ganges (11,300 m^3/s), although they carry almost similar sediment loads (550 and 590 million ton/year in the Ganges and Brahmaputra respectively) (CEGIS, 2010). The average annual water discharge contribution of the Upper Meghna River is 4,600 m^3/s, with a negligible sediment load (13 million ton/year), because most of its sediment is compensating the higher subsidence rate in the Sylhet Haor Basin (Sarker et al, 2012). Similar to the Brahmaputra, about 80% of the Ganges discharge and 95% of its sediment load are delivered to the margin during only four months, making the system extremely sensitive to this seasonal forcing (Goodbred, S., 2003). Regime type relations of the Ganges, Brahmaputra (Jamuna), and the Padma in bank-full discharge are shown in Table 5.1.

Table 5.1: Regime relations in the main river systems

River	Ganges	Jamuna	Padma (combination of Ganges and Jamuna)
Bank-full discharge (m^3/s)	40,000-45,000	45,000-50,000	75,000
Regime width (km)	2.5 (restricted) 3.7 (unrestricted)	4	3.9 (restricted) 5.2 (unrestricted)
Regime river depth (m)	6.9 (restricted) 6.5 (unrestricted)	7.1	8 (restricted) 7.8 (unrestricted)
Average regime bed slope (cm/km)	5	7.5	
Bed material, D_{50} (mm)	0.15 (Hardinge Bridge)	0.20 (Bahadurabad)	

Source: FAP 24, 1996

Fluvial, tidal, and comprehensive hydro-morphodynamics interaction in a complex, seasonal, and bidirectional sediment transport regime remains poorly examined (Wilson and Goodbred, 2015). The GBM, which is characterized as a tide-dominated delta (Seybold et al., 2007; Guo L., 2014; Akter et al, 2016), is one example of a huge system lacking data; especially morphological data, let alone a sediment budget (Akter et al, 2021). Hence it is difficult to understand and predict future developments. Special attention is required to concentrate on the estuary system, along with its floodplain and tidal plains, to know its behaviour to changes in water and sediment supply, and MSL.

The Meghna estuary is defined as an ebb-dominated estuary, whereas the other Baleshwar estuary is flood-dominated; and the rest are mixed (Haque et al, 2013). Many changes in this delta have occurred during the last few decades, including land loss and reclamation. Rahman and Rahaman (2017) have reported that 30% of the flow of the Ganges was diverted from the main channel after the Farakka Barrage construction in 1975. This large-scale reservoir trapping would probably be the cause of huge erosion in the Sundarbans Mangrove forest (Fischer et. al., 2017). Hence it is important to find the delta response in future water discharge (climate change) and sediment (due to climate change and land management in the upstream) changed scenarios along with SLR and subsidence.

More than one billion ton per year of sediment enters the system, making the delta prograde the sea at a decade-scale rate of 17- 36 m/year and century-scale rate of 4.4-9.9 m/year (Akter et al, 2016). Most of the sediment load carried by the river to the river mouth is found to be deposited north-east of the Hatiya Channel. Tides play a key role in pumping the sediment into the Meghna estuary. Tides are semidiurnal, with a slight diurnal inequality, along the coast of the Bengal Delta (including the Indian part), and the average tidal range varies from 1.5 m in the west to more than 4 m at the northeast tip of the Meghna estuary. Although the GBM delta is macro-tidal (mean tidal range > 4 m) and large tides at the coast may propagate 200 km inland (Bricheno et al, 2016), the Meghna estuary is a meso-tidal estuary, where the tidal range varies between 2 and 4 m (MES II, 2001).

Surface hydrology of the Bay of Bengal is determined by the monsoon winds, which come from the west-central part of India towards the north-east direction from the sea with low pressure, along with hydrological characteristics of the Indian Ocean. The combined effect of higher wind speed and direction and low pressure during monsoon make the water level at the Bay of Bengal higher. Tidal water levels at different locations from different sources were checked. Table 5.2 shows the seasonal water level variations along the coast. Hiron Point at the western coast shows a 0.5 m seasonal variation, whereas that of Sandwip at the northeast corner of the Bayhead has 0.9 m. The Eastern coast shows a seasonal variation varying between 0.6-0.8m.

Table 5.2: Seasonal sea level variation in the Bay of Bengal along the coast

Station	Mean Water level (mPWD)		Mean Tidal Range (m)		WL difference (m)	**Source**
	Dry	Flood	Dry	Flood		
Along Chittagong coast					1.18	http://en.banglapedia.org/index.php?title=Sea_Level_Change
In the Bay of Bengal					1.0	
Cox's Bazar	0.6	1.7	3.3	3.2	0.7	http://www.fao.org/docrep/field/003/AC352E/AC352E04.htm
Khepupara	-0.3	0.2	2.7	3.4	0.5	
Chittagong	1.8	2.6	3.1	3.2	0.8	http://tides.mobilegeographics.com/calendar/year/1231.html
Hiron Point	1.6	2.1	1.9	1.9	0.5	BITWA tidal water level
Sandwip	1.0	1.9	3.9	4.9	0.9	BWDB tidal water level data analysis
Potenga	0.1	0.7	3.1	3.8	0.6	
Chittagong	0.6	1.4	2.9	3.2	0.8	
Cox's Bazar	0.9	1.6	2.1	2.0	0.6	

5.1.3 Data Scarcity for Modelling

The GBM delta is a good example of a huge system lacking data (Masood, et al. 2015). Not even a complete momentary bathymetric data set has ever been recorded. Datasets of continuous river flow or water levels are present for a very limited number of stations. Measurements by specific organizations are available but are mostly not publicly accessible. Measurements of suspended sediment concentration (SSC) are even scarcer and typically cover only short periods. Hence it is difficult to understand the distributions and fate of river-borne sediments as well as to assess the system's reaction to future scenarios of possible river flow and sediment reduction, subsidence, and sea-level rise (SLR). Few studies are devoted to morphodynamics like delta shifting and river avulsion (Akter et al., 2016; Sarker et al., 2011; and Sarker, Akter, and Rahman, 2013). It is important to understand whether the Meghna estuary is aggrading, degrading, or tends to attain morphodynamic equilibrium in the coming decades.

River-bed slope, depth of the river at the river mouth, and mean sea level (MSL) are important parameters for understanding the long-term morphodynamic behaviour of the system. Modelling efforts would help to understand this behaviour and the impact of future scenarios including the impact of SLR. However, the required bathymetric data are local and scarce. There is no bathymetric data describing the entire system, let alone sequences of bathymetric development to validate a morphodynamic model. Still, numerical models with proven value by validated case studies may help to explore the long-term morphodynamic evolution of this ebb-dominated estuary. Here we provide results on the hydrodynamic and morphodynamic behaviour of a 1D Meghna estuary model that is affected by both tidal and fluvial processes.

The purpose of this work is to develop a morphodynamic model to explore the first-order dynamics of GBM bathymetry. Research questions are related to the time scale of the morphodynamic evolution of the system, the possible existence of (dynamic) equilibrium, the impact of river supply pulses, and the impact of SLR along with subsidence. Model results and gained insight may eventually be used as input for a more detailed 2D model (not this study). To answer those research questions, here we use a 1D morphological model with Delf3D.

5.2. Numerical Model

In this section, we present the numerical model, the geometry of the model, the initial and boundary conditions used to simulate the morphodynamic evolution of the GBM rivers. A length of 395 km river domain, mimicking the length from Bahadurabad to the river mouth, and 205 km of the marine domain are considered for this work. The channel is considered shallow (depth/width<< 1) and long (width/length << 1).

5.2.1. Model Description and Numerical Method

Delft3D-FLOW module is a multidimensional (2D or 3D) hydrodynamic and sediment transport simulation program that calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a curvilinear, boundary fitted grid (Hibma, 2004, van der Wegen, et al, 2008). One cell width was considered in this study for 1D modelling work. To reduce computational time and resources, a depth-averaged approach was applied, that is the governing equations of the same model are integrated over depth. This model solves two-dimensional vertically (2DH) integrated shallow-water equations coupled with advective-diffusive transport and includes sediment transport formulations for cohesive and non-cohesive sediments. Van Rijn (1993) formulae are used by default for non-cohesive sand transport and Partheniades-Krone formulae (Partheniades, 1965) were used for calculating the fluxes between the water phase and the bed for cohesive mud.

5.2.2. Model Geometry, Boundary, and Initial Conditions

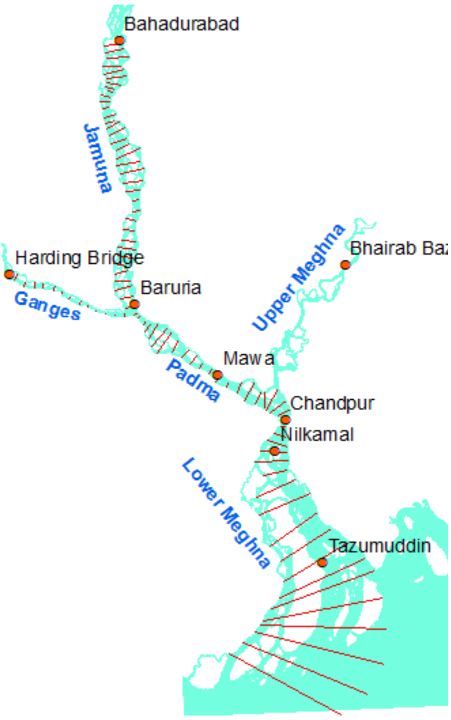
5.2.2.1 Model Geometry

The shape of the estuary depends amongst others on its hydraulic regime. The geometrical features of tide-dominated estuaries may be described in exponential relations, based on the width of their river mouths (Seminara et al., 2010; Toffolon and Lanzoni, 2010). Haque et al (2013) found that some of the estuaries in the GBM delta can be described by exponential relations, and some by logarithmic relation or combinations of both. They defined the Meghna Estuary as ebb-dominated, as it carries 91% of the freshwater flow to the estuarine system. They suggested that the whole length of the Meghna could be fitted with an exponential relationship.

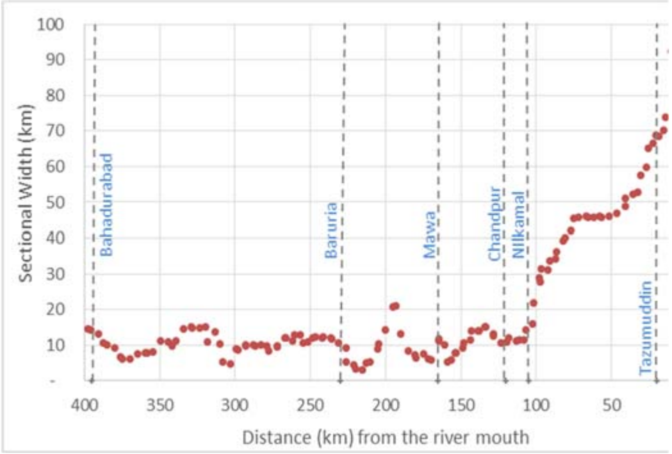
To create an equation for the Meghna estuary plan form, we adopted a simple method using satellite image and GIS techniques. The width was manually extracted from dry season satellite images, shown in Figure 5.2 (A), considering only the hydraulically active channel width. The presence of islands was considered, i.e. the width obtained included islands in the river and estuary that would be (partly) flooded during high river flow. The sectional width is shown in Figure 5.2 (B) indicates that the river expansion occurs from Chandpur. The other reach of the river (Bahadurabad to Chandpur) until about 300 km downstream of Bahadurabad shows a varying width, with an average of 6-14 km. The mean width of 8 km for the downstream Indian part Brahmaputra River was also mentioned by Goswami (1985) and Datta and Singh (2004), as mentioned in Fischer et al (2017). Hence a constant width from Bahadurabad to Chandpur along with an exponentially increasing width from Chandpur to the river mouth was considered for this study, Figure 5.3 (C). Then a constant width was deliberately considered in the sea part, from the river mouth to the downstream sea boundary.

It is to be mentioned that the measured width (figure 5.2 B) includes islands and the modelled width does not (Figure 5.2 C).

A. Delineated boundary from satellite image



B. Varying sectional width



C. Considered width for the model

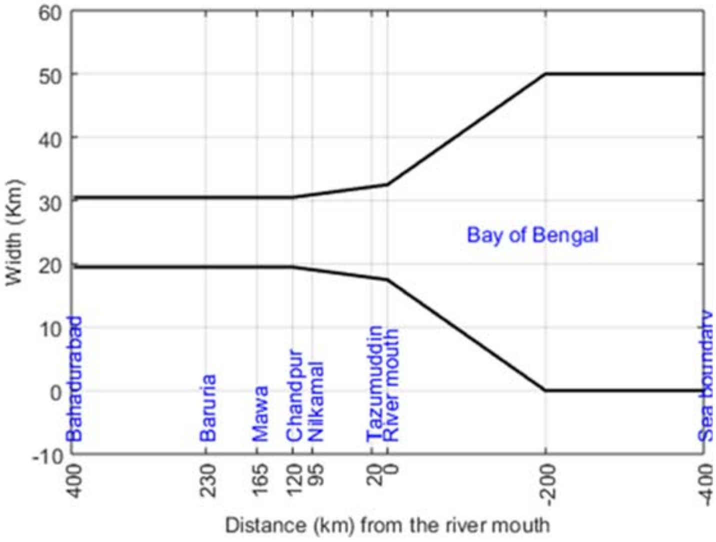


Figure 5.2: Sectional width (B) generation from the Brahmaputra- Padma-Meghna river boundary based on a satellite image (A). [Brahmaputra (Bahadurabad to Baruria), Padma (Baruria to Chandpur), Meghna (Chandpur to river mouth)], and (C). Imposed width for the model expands from Chandpur to the river mouth.

The initial bathymetry was more problematic due to a lack of data. Various numerical simulations were done considering an initial linear bed profile under different slopes and mouth depths. Lacey (1930) derived regime relations based on the data from the irrigation canals flowing through sandy materials in Punjab for designing a stable canal. According to the regime theory, the bed slopes of the Ganges and Brahmaputra rivers are 5 cm/km and 7.5 cm/km respectively although the bed profile varies from river to river. We start the work with a linear bed profile from 3 cm/km, with an initial depth of the river mouth of 6 m. All elevation data shown in this chapter are in Public Works Datum (PWD), which is considered 0.46 m above the MSL. This datum was established in India under British rule and brought to Bangladesh during the Great Trigonometric Survey in the 19th century (1802-1871).

5.2.2.2 Boundary conditions

As the system is carrying the combined flow of the Ganges and Brahmaputra rivers to the Bay of Bengal, combined daily water discharge data of Hardinge Bridge in the Ganges and Bahadurabad in the Jamuna was considered. Also, the average value of associated sediment discharge (based on the rating curve generated from FAP24 measurements in 1996) concentrations of both the rivers were used at the upstream boundary, assuming that both the sections have the same behaviour. After the commissioning of the Farakka Barrage in the Indian part of the Ganges in 1975, the dry season discharge in Bangladesh was substantially reduced, but the flood flow remained similar. Hence temporally varying discharge data from 1981 to 1983 were used for this study. Figure 5.3 shows the discharge and sediment hydrographs of 1981. In the downstream boundary of the model, no cohesive sediment input was considered, as the water depth is large and tidal motion would not transport fine sediment landward. However, an equilibrium sand concentration profile was deployed at the seaward and landward inflow boundaries. A morphological time scale factor was used to speed up the morphological changes without having a significant impact on the hydrodynamics (Roelvink, 2006).

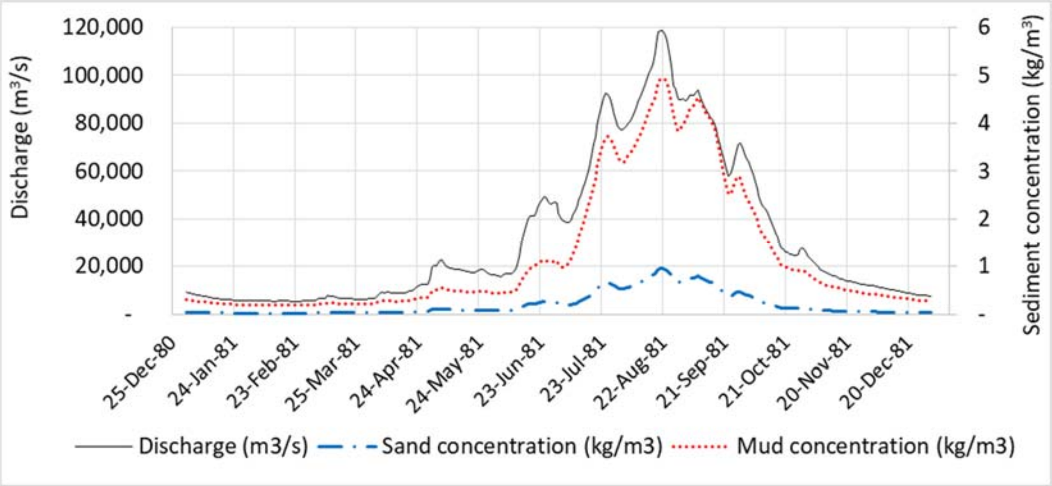


Figure 5.3: Discharge and sediment hydrographs at the upstream river boundary for 1981

We follow suggestions by Lesser (2009) to derive a harmonic, schematized morphological tide forcing the model to allow for gradual and harmonic developments. Lesser (2009) determined that a 7-20% larger amplitude of the largest constituent “principal lunar semi-diurnal” M2 tide can be considered the morphological tide. An artificial diurnal component (C1) can also be added to the M2 tide to represent the morphological tide. Lesser (2009) has suggested the amplitude and phase of the C1 tide as a function of diurnal components (O1 and K1), where these two diurnal tides are assumed to be important for the morphological simulation. The amplitude and phase of C1 as symbolized by C_1 and φ C1 are computed by $C_1 = sqrt(2O_1K_1)$ and $\varphi\ C1 = (\varphi O1 + \varphi K1)/2$ respectively. Therefore, a combination of M2 and C1 tides at the sea boundary was used for this study. Table 5.3 shows the characteristics of the tides in the Bay of Bengal considered for the model based on Akter et al (2021).

Table 5.3: Characteristics of the tides in the Bay of Bengal

Tide	Frequency (deg/hr)	West boundary		East boundary	
		Amplitude (m)	Phase (deg)	Amplitude (m)	Phase (deg)
M2	28.9841	0.8	285	1.06	303
C1	14.49205	0.36331804	164	0.14282857	179.56

Sediment grain size to the first-order controls settling velocity, with the requirement that settling velocity relationships is non-linear due to coagulation or flocculation processes in case of fine and muddy sediments. Two sediment classes were defined, cohesive mud and non-cohesive sand. The median diameter of sand is considered to be 0.2 mm; whereas the settling velocity of mud is 0.1 mm/s. The critical bed shear stresses for erosion and erosion parameters were considered to be 0.1 N/m^2 and 0.0005 kg/m^2/s respectively. Initially, a constant Chezy's value (C=100 m$^{0.5}$/s) for bed roughness was considered; later C-values were adjusted through several simulations. A total length of 800 km (395 km river part and 405 km sea part) with a grid size of 5 km was adopted for this study, as shown in Figure 5.2C. A flat bottom in the estuary part, from Chandpur to the river mouth, was considered.

5.3. Results

5.3.1. Initial Hydrodynamics of the Model and Comparison with Available Data

Many project works have been carried out in the study area and a series of measurements were taken during those study periods. But due to improper management or for considering their business in the future, those data sets have become publicly unavailable or completely inaccessible. Water level data in the riverine and marine area are one of the most available data. The available water level data within the study reach (Mawa, Chandpur, Nilkamal, and Tazumuddin as located in Figure 5.1 along the Brahmaputra-Padma-Lower Meghna rivers system) for the same period were compared with the model results considering morphodynamics. Selected locations at Tazumuddin, Nilkamal, Chandpur, and Mawa were considered to be 20 km, 105 km, 120 km, and 165 km respectively upstream from the river mouth, as shown in Figure 5.4. The average water level of daily high and low tides levels (observed) are considered for comparison with the model results, which is found in every 30-minute time step. Mainly water level and tidal ranges of observed and modelled datasets were compared for finding the best simulation for considering unknown model parameters.

5.3.2. Model Adjustment with Slopping Bottom Profile

Figure 5.4 shows the spatial distribution of the river bed with varying tested slopes and the planform geometry of the model. This width averaged bed level is considered for the initial model input, although local scour levels in the three rivers were observed lower than -40 m PWD. A comparison of time series water levels suggests that the slope of 3 cm/km and 4 cm/km have a good match with the observed data. Hence we used these two slopes for our next simulations for selecting a better match. Figure 5.5 shows the spatial distribution of seasonally mean water level and tidal range. The model under-predicts the tidal range during the flood season but reflects the dry season tidal range fairly well. We attribute this to the width averaged approach of the model, whereas, in reality, the profile would include channels and floodplains resulting in somewhat different tidal dynamics and a better match to the flood season tidal range.

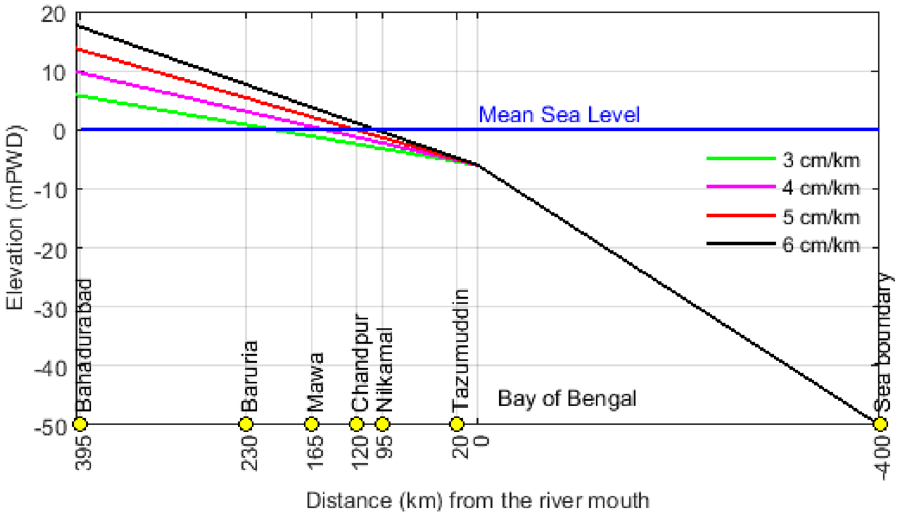


Figure 5.4: Changing river bed slope and spatial distribution of the selected locations

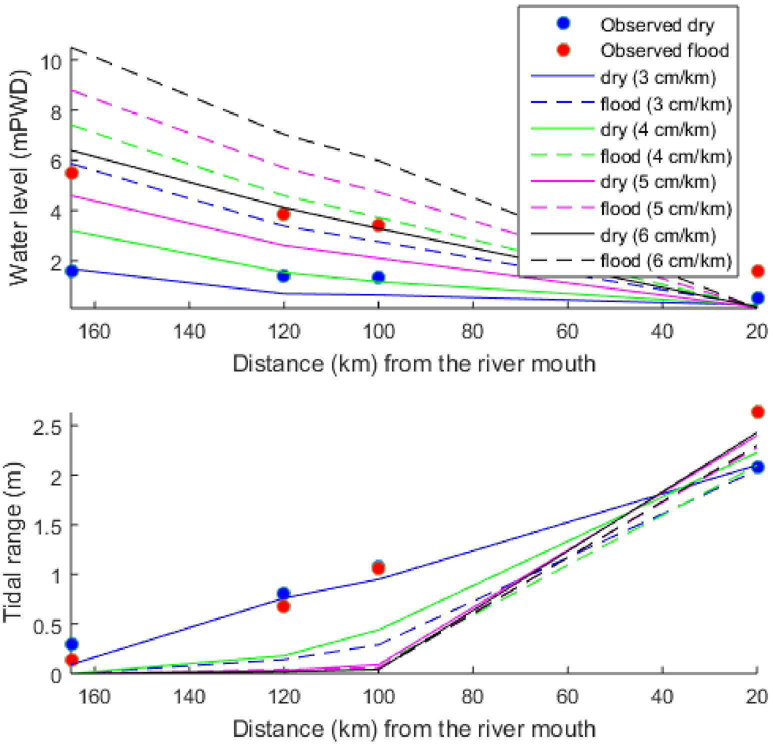


Figure 5.5: Spatial distribution of mean water level and tidal range in dry and flood seasons

A seasonal variation is spotted in the observed water level at the river mouth as shown in Figure 5.5 (top panel). Although we have found seasonal variation the upstream, no variation at the river mouth in the computed water level data. Accordingly, the next simulation will be done after adopting seasonal variation in the sea boundary.

5.3.3. Model Adjustment with Seasonal Sea-Level Variation and Its Effect

Simulations described in the above sections did not include seasonal sea-level variation, whereas the Bay of Bengal has a mean seasonal variation, as discussed in earlier sections. Hence it was needed to introduce a seasonal variation in the downstream boundary of the model. After analyzing water levels at different locations of the Bay of Bengal, a harmonic tide with 0.35 m amplitude (a total of 0.7 m seasonal variation) was considered for the model.

Figure 5.6 shows the water level comparison in different model simulations after incorporating seasonal variation in the sea with the observed water level. Observed time series water levels were compared with model results from 3 cm/km and 4 cm/km bed profiles without seasonal water level variation in the sea (Figure 5.5), and that of seasonal variation at the sea boundary (as shown in Figure 5.6). A comparison of Figure 5.5 and Figure 5.6 exhibits the spatial variation of average seasonal water level and tidal range. Before introducing seasonal variation in the sea boundary, the results show no change in the sea level. But after incorporating seasonal variation, model results show a worthy match with the observed water levels.

Nevertheless, the dry season water levels at Tazumuddin, Nilkamal, and Chandpur were underestimated in the results, for both the 3 cm/km and 4 cm/km river bed profiles. Computed dry and flood seasonal water levels at Mawa show overestimation for both cases. Besides, flood seasonal water levels at the river mouth display undervalued. However, computed seasonal average water level from results of 4 cm/km shows a better match with that of observed water level data.

Seasonal variation in the tidal range is already noted in the computed data for both 3 cm/km and 4 cm/km bed profiles. Tidal ranges at Tazumiddin (20 km upstream from the river mouth) in the flood season are higher than that of dry seasonal tidal ranges for both cases. But, no seasonal tidal range variation was seen at Mawa, whereas Mawa has seasonal tidal range variation, as noted in Figure 5.6 (bottom panel). Along with water level results, tidal range data also indicate a good match for the bed profiles of 4 cm/km. Hence, these profiles will be used for our next simulations.

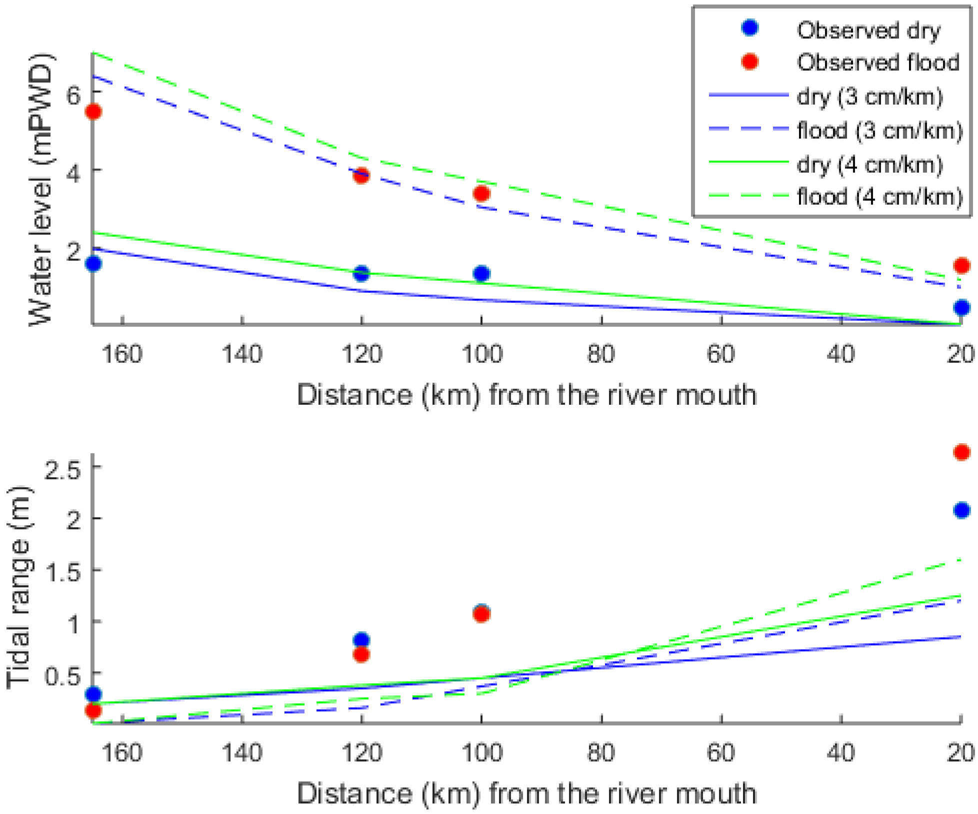


Figure 5.6: Spatial distribution of mean water level (top panel) and tidal range (bottom panel) in dry and flood seasons after introducing seasonal variation in the sea boundary

To match seasonal water level and tidal range at the river mouth, we will adjust the model input with changing water depth at the river mouth. We have used earlier simulations considering 6m depth at the river mouth.

5.3.4. Model Adjustment with River Depth at the Mouth

Figure 5.7 shows the impact of varying depths of 5.5 m, 6 m, and 6.5 m at the river mouth, following a bed slope of 4 cm/km. Still, the flood water levels as shown in Figure 5.7 (top panel) in the upstream are higher than the observed ones. Even, dry season water levels at Mawa are overestimated. For reducing the water levels, we will play with a bed roughness of 100 $m^{0.5}$/s. Moreover, the pattern of computed tidal range as shown in Figure 5.7 (bottom panel) has come to a good match, only those are a bit dropped than that of the observed. Computed results show that consideration of 6 m and 6.5 m have a good match with the observed data. Based on this sensitivity, we chose 6 m at the river mouth for our next computations.

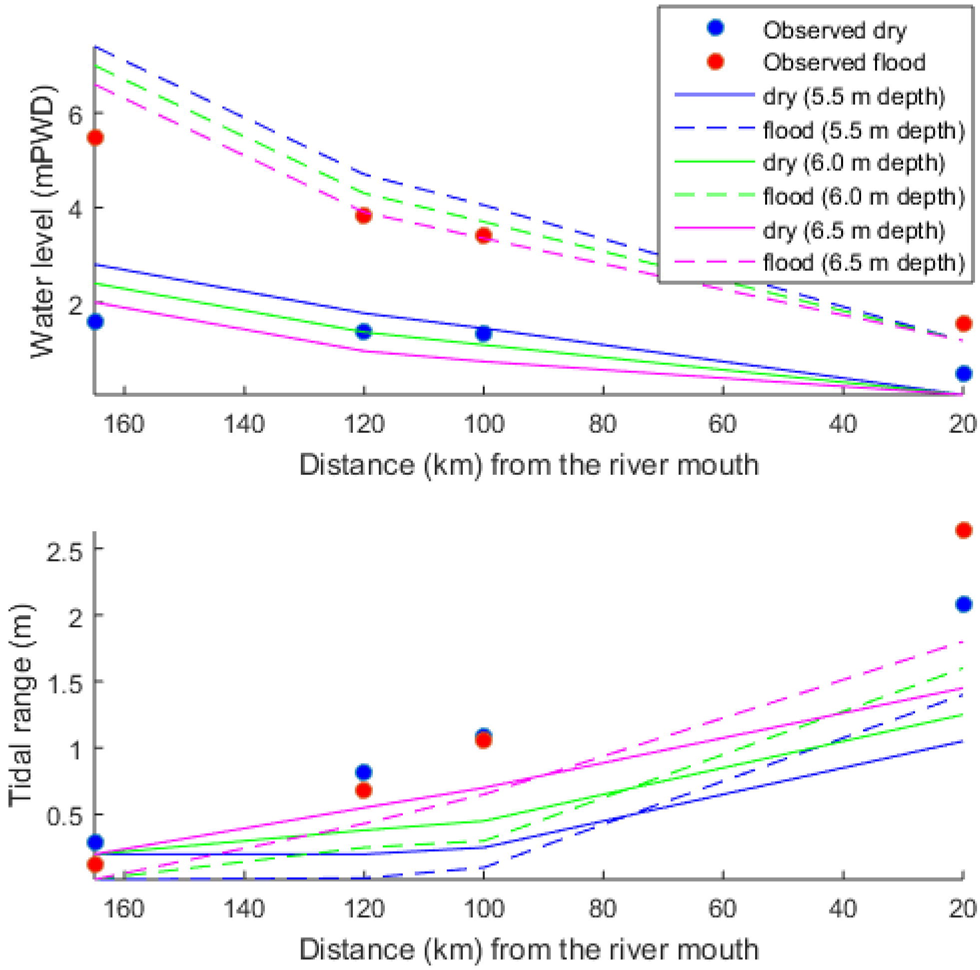


Figure 5.7: Spatial distribution of seasonal mean water level (top panel) and tidal range (bottom panel)

5.3.5. Model Adjustment with Bed Roughness

Sensitivity results with different Chezy's roughness values (75, 100, 125, and 150 $m^{0.5}/s$) are shown in Figure 5.8. River bed slope of 4 cm/km with 6 m depth at the river mouth and MSL of 0 mPWD have been considered for this section, although sensitivity with MSL will be discussed in the subsequent section. Model results show that simulation with C= 150 $m^{0.5}/s$ has the closest (intimate) match with observed water level (top panel) and tidal range (bottom panel).

Till now, computed water levels at Tazumuddin are underestimated, but the seasonal variation at this location is already achieved. Flood seasonal water levels at Mawa, 165 km upstream of the river mouth, are overestimated. In contrast, computed tidal ranges have a good match with the observed data. To improve the water level at Tazumuddin, we will play the model by changing the MSL; whereas, we used 0 mPWD MSL in the earlier sections.

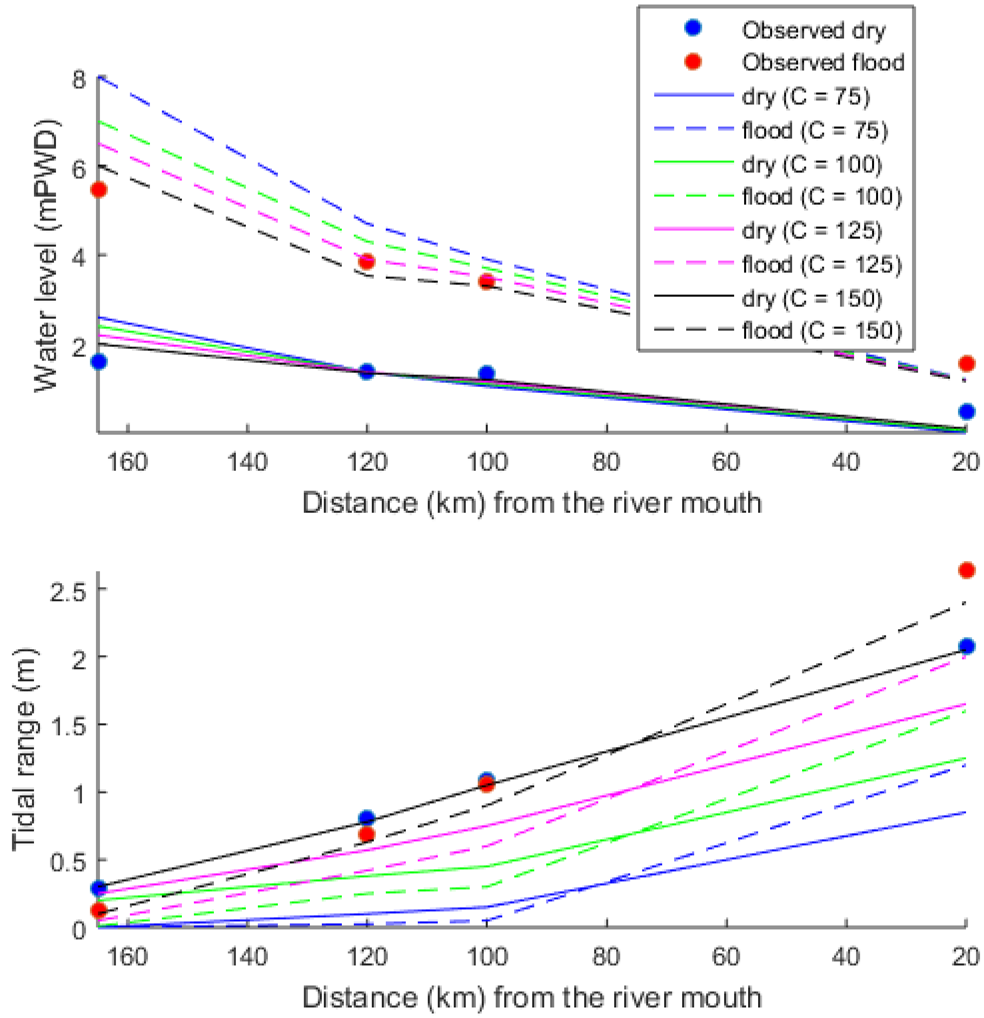


Figure 5.8: Sensitivity with bed roughness (Chezy's value)

5.3.6. Model Adjustment with Changing Mean Sea Level

MSL was verified based on the observed tidal water level data at Tazumuddin, 20 km upstream of the river mouth, as shown in Figure 5.1. Figure 5.9 shows different computed results from changing MSL at 0.0 mPWD and 0.5 mPWD used for simulations. It is to be mentioned that 0.46 mPWD indicated 0 MSL. Adjustment with changing depth at river mouth shows similar behaviour in the change in the tidal range that of changing MSL. Consideration of 0.5 mPWD shows a good match with mean seasonal water level (top panel) and tidal range (bottom panel) variation.

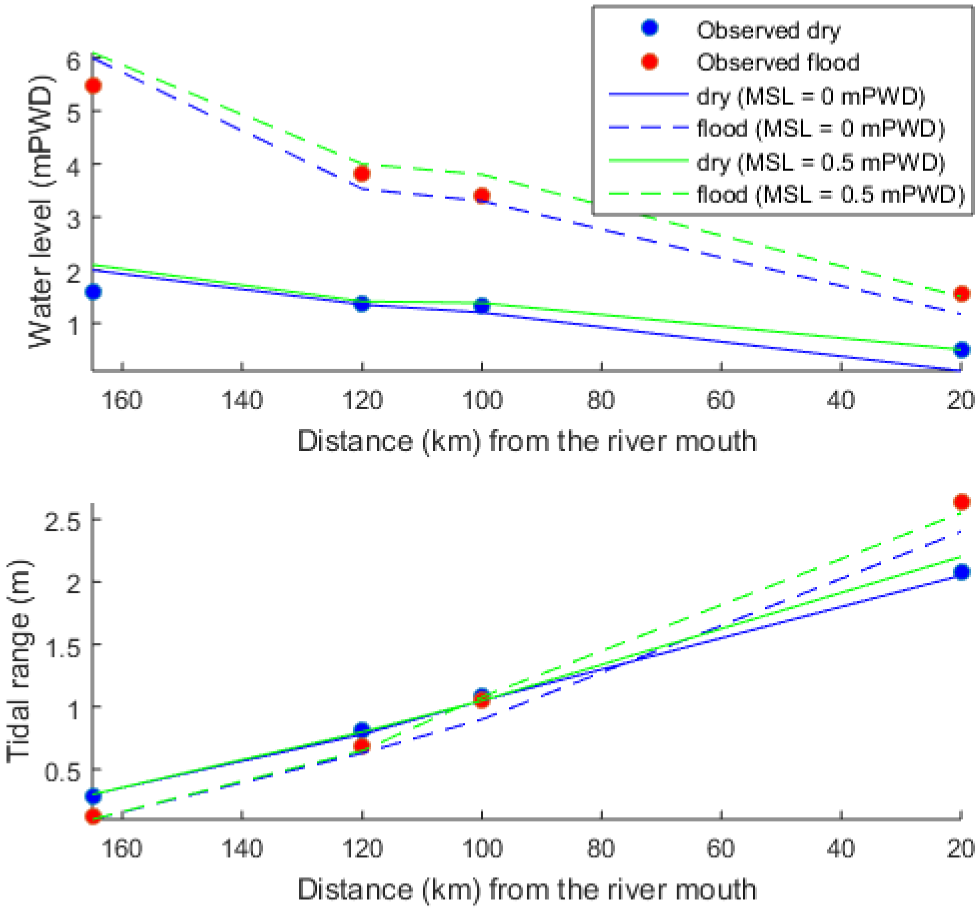


Figure 5.9: Sensitivity with changing mean sea level

5.3.7. Long-term Morphodynamic Changes

5.3.7.1. Decade scale Morphodynamic Changes

Figure 5.10 shows the bed level evolution after 50 years, 70 years, and 100 years. Overall, the bed profiles show deposition both in the river and marine reaches. Initially, the river bed profile was found to be eroded (within the first few years that is not shown in Figure 5.10), probably due to morphological adjustment with the boundary forcing. Deposition occurred in the mouth of the estuary just after Nilkamal, where the river geometry has started expanding. In the computed results, the sedimentation front after the river mouth was found to be net propagating seaward more than 50 km in 50 years. No sediment was leaving the domain, as we have considered no inflow or outflow at the sea boundary.

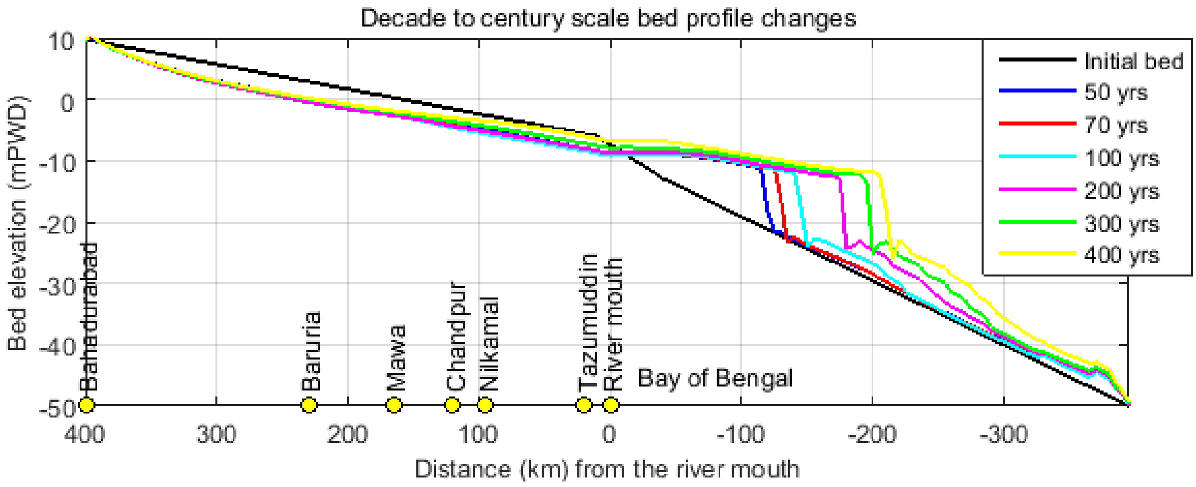


Figure 5.10: Bed profile changes in a decade to century-scale

The estuary corresponds to an area with bars/islands in reality and cannot be reproduced by a 1D model. But the sequential riverbed up-gradation found in the computed results may indicate shallow water depth in that region. For maintaining the required water slope between a specific location and the river mouth, the estuary area may develop a series of bars/islands.

5.37.2. Century scale changes

Regarding century-scale bed profile changes, as shown in Figure 5.10, continuous bed level aggradation is observed in the computed results. A propagating sedimentation front (delta front) is also clearly observed in this long-term simulation until the end of the simulation. Bed-level aggradation in the model indicates a shallower depth of the river, and hence in reality it may turn to widen the river width, which cannot be reproduced in this 1D model where the width was constant in the outer reaches (Figure 5.2C). Or else it may result in avulsion in the delta system. River bed aggradation as well as water level rise in the estuary will have an influence on tides propagation inside the system.

5.4. Discussion

5.4.1. Morphodynamic Equilibrium

Morphodynamic equilibrium indicates a morphodynamic and hydrodynamic stable state along with its spatially uniform bed shear stress (van der Wegen et al., 2008; Guo et al., 2014b). Wright and Thom (1977) defined the morphodynamic equilibrium as the result of mutual adjustment of topography and fluid dynamics concerning sediment transport. This definition was also applied for identifying morphodynamic equilibrium for this modelling study.

In reality, there will never be equilibrium as the profile keeps expanding. However, in this study, the model has been run for 400 years and no equilibrium bed profile was found within this period under unchanged boundary forcing. Morphological development became significantly slower after 200 years (Figure 5.10). Hence we cannot consider any equilibrium bed profile within the simulated period in this long-term simulation, as shown in Figure 5.10 (century-scale bed profile changes).

5.4.2. Changes with Sea Level Rise and Subsidence

Figure 5.10 shows the time evolution of the computed bed under the no climate change scenario. No morphological equilibrium was found to reach within 400 years. The computed bed profile may differ considerably from reality due to width variations along with the profile, bend scour and island development in wider parts in reality.

SLR and subsidence in the GBM delta have been mentioned in numerous studies. These two parameters undoubtedly are prevailing in this system. Goodbred and Kuehl (2000) show the response of the Bengal delta during the Holocene. However, an assumption of 0.006 m/year SLR and 0.002 m/year subsidence were considered for this study for 100 years of climate change scenarios. The changing profiles of the SLR (initially slow, later with a faster rate) and subsidence (linear) considered for the model are shown in Figure 5.11.

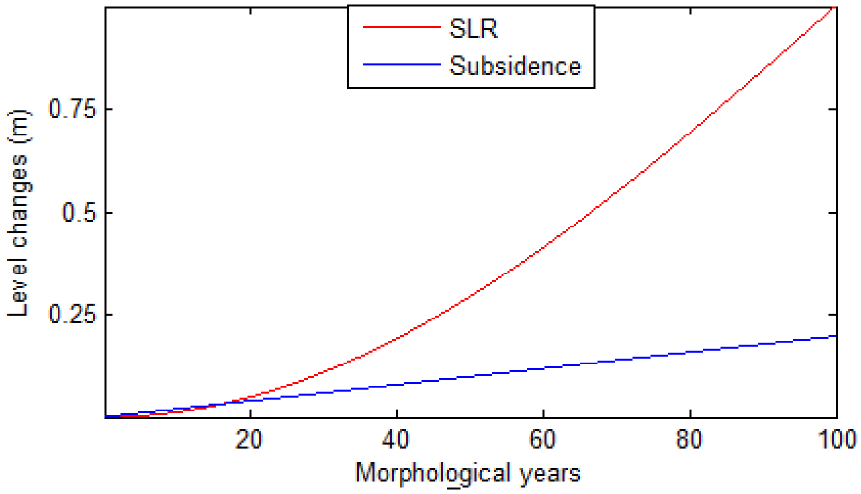


Figure 5.11: Level changes (m) in 100 years for sea-level rise and subsidence

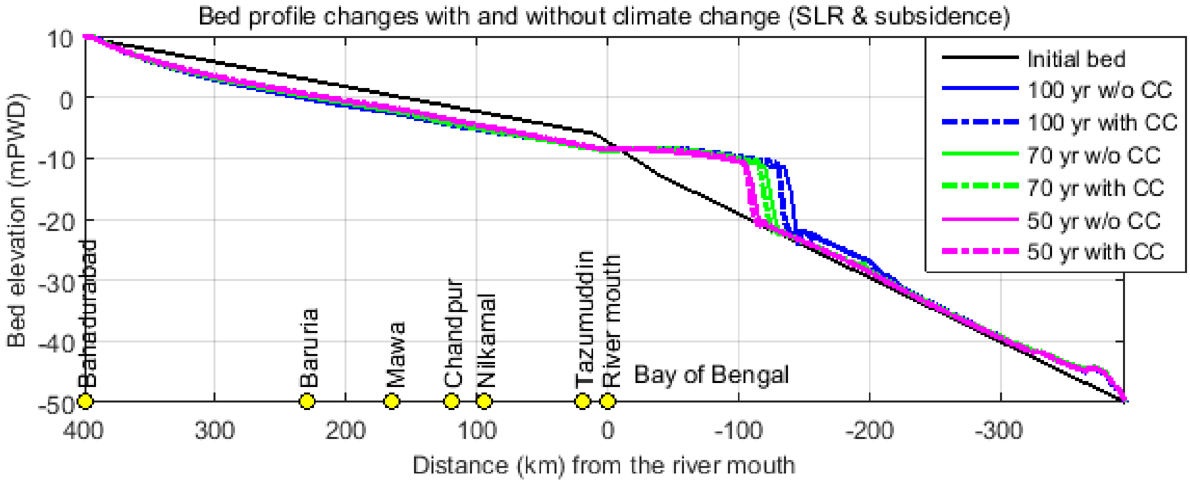


Figure 5.12: Bed profile changes with and without (w/o) climate change (sea level rise and subsidence) scenario

Figure 5.12 shows the bed profile changes with and without climate change scenarios starting from the initially linear bed. The aggradation rate would be slightly higher in the climate change scenario considering SLR and subsidence. Under without a climate change scenario, the bed development would be higher, especially just upstream of the river mouth. The apex of the river mouth would develop more vertically and horizontally. On the contrary, under the SLR and subsidence scenario, the delta front would propagate less by a few kilometers. In the upper reaches, the bed would aggrade by a few centimeters, whereas the bed would have less deposition near the sedimentation front. But, the delta front would transgress a few meters towards the land.

5.4.3. Consequences of Bed Level Changes

This study has introduced a simple methodology that can describe a big complex system with minimum data and information. Especially this methodology is applicable where there is limited data available. A simple 1D modelling exercise helps assume the system parameters. These parameters can be used for the 2D modelling exercise. However, this study reveals that 1D modelling is capable of producing hydrodynamic similarities with the observed datasets. It also indicates that the total system may not reach equilibrium even after 400 years. The bed level changes can be described in many ways.

Firstly, the rapid bed level aggradation in the riverine system would accelerate the avulsion process from the existing Lower Meghna River to its distributaries. Secondly, the modelled bed level changes are expected (intentionally) to be higher than in reality, due to a lack of consideration of the floodplain and tidal plains in the modelling system, because a substantial amount of sediment would be deposited in the floodplain and tidal plains. Thirdly, riverbed aggradation would also be translated as width widening with channel bar formation. Geological characteristics of the river bank or strong riverbank protection works may not allow the river to be widened, where deep scouring is expected. Fourthly, the rivers' confluences play an important role in river widening along with scours and bar formation downstream. After the Ganges River merges with the Brahmaputra at Baruria, a confluence scour is observed. Similarly, at Chandpur, where the Upper Meghna River merges with the Padma, a confluence scour is observed. Moreover, the protrusion scours at Chandpur due to Chandpur town protection works at the left bank of the river has an additional contribution to the scour.

5.4.4. Sediment Changes Scenario

The computed results are shown considering similar sediment input to the system. But in the future, upstream land and river management may change the sediment scenario. More sediment trapping through sediment management would reduce sediment in the downstream river system. Under this scenario, riverbed degradation is obvious, along with localized scour and the widening of estuaries. On the contrary, increased sediment in the downstream river system, due to poor sediment management in the upstream, would aggrade the riverbeds at a higher rate. As a consequence, the river and estuary response would be relatively quick and delta progradation would be visible.

5.4.5. Model Limitation

The numerical model is capable of representing reality with a set of equations based on several assumptions. All modelling works have their limitations related to fix planform geometry, no tidal plain/ floodplain, no island in the estuary, no distributary, and many more. Even though we try to consider the real geometry of the estuary, we made a fixed planform geometry for the model. We have not considered any floodplain and tidal plain for the system, where a substantial amount of river-borne sand and mud deposits. The presence of islands in the estuary plays an important role in distributing flow in the mouth area.

This 1D modelling work is expected to catch the millennia time scale dominant morphodynamics of the entire system, while a 2D modelling work (e.g. Akter, et. al., 2021) includes processes on shorter timescales (~decades) such as channel-shoal pattern dynamics, floodplain (Brahmaputra and Padma rivers), and tidal plain (Lower Meghna river) deposition, and distributaries of all rivers.

Another limitation of this work is sediment size distribution. We have considered only two types of sediment flow, which is not enough to represent the system. Even, vertical sediment stratification, which is another important controlling factor for the river profiles, is missing in this work. Wind and wave forces have a significant influence on tides in the sea. This 1-D model does not include any wind and wave forces. In addition to this, deltaic and tectonic subsidence is neglected in this work.

5.5. Conclusions

Our modelling exercise was able to explore the morphodynamic development of a large system on the time scale of millennia. The computed results suggest that the consideration of MSL at the Bay of Bengal at 0.5 mPWD would produce a matching hydrodynamic condition with the observed data. The introduction of seasonal variation of 0.7 m in the Bay of Bengal improves this match. Where we have a lack of river bathymetry data, this modelling work suggests that the use of a 4 cm/km bed slope along with 6 m depth at the river mouth would represent the system.

In reality, there will never be equilibrium as the profile keeps expanding. The long-term morphodynamic behaviour of the GBM rivers with a simple 1D model suggests that it prograded within the simulated period of 400 years. Although initially, the progradation rate is higher until 200 years, later the rates slow down. The riverbed in the system would increase with and without SLR and subsidence scenarios in the coming centuries. With climate change scenarios, the bed aggradation in all rivers would be less than that of without the climate change scenario. Additional sediment introduction in the existing setup of the system would enhance the riverbed aggradation rates. In that case, the delta is expected to prograde at a higher rate. In contrast, reduction in sediment from upstream may cause river degradation along with localized scour and widening of the estuary depending on the local geo-morphology.

Chapter 6

Process-Based Modelling Deriving a Long-Term Sediment Budget for the Ganges-Brahmaputra- Meghna Delta, Bangladesh

Fluvial, tidal, and combined hydro-morphodynamics interaction in a complex, seasonal, sediment transport regime has been the subject of extensive research. It becomes particularly challenging when there is limited data. The Ganges-Brahmaputra-Meghna (GBM) Delta is one example of a huge system lacking data. Bathymetric data simultaneously covering the rivers and estuaries is hardly present, let alone sequences of bathymetries or a system-wide sediment budget. Hence it is difficult to understand and predict future developments. This research aims to make a sediment budget for the GBM delta with a process-based model. It is a first-ever sediment budget simulation for the GBM system. A process-based morphological model, Delft3D, has been used to reproduce the bathymetric evolution over time and the associated sediment budget. This chapter demonstrates the possibilities for the application of a robust modelling system to assess the morphodynamic evolution and sediment budget and pathways. The Ganges and Jamuna rivers carry sediment load in the range of 216-1038 million ton/year and 80-228 million ton/year respectively. The total accumulation in the estuary system is 1150 million ton/year, out of which more than eighty percent of sediment is in suspension. The model results show that about 22% of the total sediment coming into the system is deposited in the floodplains and tidal plains and causes river morphology changes. The rest of the sediment is lost to the pro-delta, to the deep ocean bed, or leaves the domain. The results also indicate that the Padma, Gorai, PussurArial Khan, Upper Meghna, Mongla-Ghashiakhali, Passur-Sibsa, Bishkhali, Shahbajpur channel, and Lower Meghna, Tentulia Channel, and Arial Khan rivers are mainly in the aggrading phase, whereas, the Baleshwar, Ganges, and Jamuna, and Baleshwar are in the degrading phase. This particular delta model offers many opportunities to compare with sediment data, where it deals with a poorly surveyed area.

This chapter is based on:

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6.1 Introduction

6.1.1 Modelling Sediment Flux to Ocean

Rivers supply sediment from their catchment into the ocean (Owens, 2007). Under conditions of ample sediment supply part of these sediments will deposit in the floodplain and estuarine plain heightening the local bathymetry and prograding the river delta (Sarker, et al. 2011). Various studies have attempted to quantify changes in historic river sediment supply to coastal plains. Kondolf, et. al. (2018) have worked on changing the sediment budget of the Mekong River. Owing to their general nature and assessment of a broad range of large-scale systems, these studies' methodologies apply an aggregated model approach to estimate sediment fluxes. In most large-scale delta systems, data is lacking on channel geometry and bathymetry, or water and sediment fluxes throughout the delta distributary network. Measurements are typically made in the main tributary at the 'apex', i.e. near to the off-take of the river. The occurrence of dispersal of sediment downstream remains often largely unrecorded. Even less known is the process of reworking of sediment from offshore river plumes back into the estuarine plain. This study explores these dynamics for the Ganges-Brahmaputra-Meghna (GBM) Delta in Bangladesh. In particular, this study focuses on deriving a sediment budget analysing the distribution of river-borne sediment into the GBM Delta and the ocean.

High-resolution, process-based models and approaches may reveal a more nuanced and detailed image of sediment dispersal in deltaic systems taking into account more specific, local conditions both over time and in space (Achete, et. al. 2015 and 2017). However, an often assumed drawback of these models is that they are also in need of more detailed data for model setup, calibration, and validation. In many deltaic systems worldwide, data is lacking on channel geometry and bathymetry or water and sediment fluxes throughout the delta distributary network. Data on the evolution of these parameters over various time scales are even more scarce.

Due to rapid developments in stable numerical schemes over the past decades, exciting advances in two-dimensional depth-averaged (2-DH) numerical models of river morphodynamics have taken place (Mosselman and Le, 2015). Numerical models help to create a unique virtual laboratory system including a flexible complexity of processes. Examples of a schematized approach are studies on the importance of cohesive sediments on delta formation (Edmonds and Slingerland, 2010) or the effects of waves on mouth bar growth (Nardin and Fagherazzi, 2012). In a more realistic setting, the GBM Delta is a good example of a huge system lacking data (Masood, et al. 2015). Not even a complete bathymetric data set has ever been recorded. Datasets of continuous river flow or water levels are present for a limited number of stations. Measurements of suspended sediment concentration (SSC) are even scarcer and typically cover short periods. Hence it is difficult to understand the distributions and fate of river-borne sediments as well as to assess the system's reaction to future scenarios of possible river flow increase/decrease and sea-level rise.

Gelfenbaum et. al., (2009) predicted sediment transport pathways and delta morphological response to changes in sediment supply after the expulsion of two dams in the Elwha River in Washington State, USA. Elmilady et.al. (2019) and Ganju and Schoellhamer (2010) skillfully reproduced observed decadal timescale morphodynamic developments in San Francisco North Bay (California, USA) and predicted the potential impact of climate change. Guo et al. (2014) focused on exploring the effects of tidal asymmetries, river discharge, and river-tide interaction in governing residual sediment transport and associated long-term estuarine morphodynamics in the Yangtze estuary (China).

This study explores the question to what extent high resolution, process-based modelling is suitable for deriving a trustworthy sediment budget in a data-scarce environment taking the Ganges-Brahmaputra-Meghna (GBM) delta in Bangladesh as a case study. More specifically, this research aims to explore decadal trends in sediment pathways and morphodynamics for the GBM delta utilizing a process-based morphodynamic model. The outcome of this study will potentially reveal governing processes and pave the way for the application of the proposed methodology in other case studies that will specify, quantify and qualify the results of more aggregated modelling approaches.

6.1.2 The GBM Delta

The GBM catchments together form one of the largest riverine sources of water and sediment to the world's oceans (Akter, et al, 2016; Goodbred and Kuehl, 2000a, 2000b). The GBM basins encompass a total area of 1.7 million sqkm including an area in India 64%, China 18%, Nepal 9%, Bangladesh 7%, and Bhutan 3% and influence the daily life of at least 630 million people (FAO, 2016). The three catchment areas converge in Bangladesh into the Lower Meghna River and drain into the Bay of Bengal (BoB) through several distributary channels; Tentulia, Shahbajpur, and Hatiya (Figure 6.1). In this particular work, the name of the Brahmaputra River is replaced by the Jamuna River. The Jamuna is the hydrologically unique identity of the Brahmaputra River downstream (from Bahadurabad) after diverting water to the Old Brahmaputra River in the central and eastern regions of Bangladesh (Figure 6.1). Jointly these three main rivers carry about 1.06 billion ton of sediment every year (Goodbred and Kuehl, 2000a, 2000b; Sarker, et al. 2011; Akter, et al. 2016), which is the world's largest sediment load of any river (Milliman and Syvitski, 1992), out of which 80% is delivered during the four monsoon months (June, July, August, and September) (Goodbred and Kuehl, 2000a, 2000b; Sarker, et al. 2011; Milliman and Syvitski, 1992; Coleman, 1969). During the other months, tides play a key role to redistribute the sediment deposited in the river mouth (Rogers et al., 2013). That huge amount of sediment has caused the delta to heighten and prograde. In this study, we focus on the part of the delta in Bangladesh, comprising about ~70% of the entire delta plain. The northern part is completely fluvial, whereas the southern part is coastal (**Figure 6.1**).

Fluvial, tidal, and combined hydro-morphodynamics interaction in a complex, seasonal, and bidirectional sediment transport regime remains poorly examined (Wilson and Goodbred, 2015). The GBM, which is characterized as a tide-dominated delta (Seybold et al., 2007; Guo L., 2014; Akter et al, 2016), is one example of a huge system lacking data, especially morphological data, let alone a sediment budget.

Huge amounts of sediment are stored in the Meghna Estuary during monsoon months carried by the GBM rivers (Sarker et. al. 2011, 2013) and the tidal effect becomes inactive against these strong river flows. But during the dry period, when the river flow is weaker, tides become very active and due to their circulation process, tides bring sediment to the western estuaries from the eastern Meghna Estuary. The main source of sediment in this study domain is from the eastern Meghna Estuary through tidal circulation processes. In reality, a major part of these sediments is lost in the Swatch of No Ground (SNG), which is reported to be a 14-km-wide deep-sea canyon in the BoB. So, in addition to the description of Bhattacharya and Giosan (2003), this research also finds that Bangladesh is a composite system, where different portions of the delta are morphologically distinct and controlled differently by fluvial, wave, or tidal processes.

Sand distribution from south of Bhola and Patuakhali districts, where the delta is presently active, slows down to the east. In the same line, the maximum fraction of sand is observed in the south of Bhola and the minimum at and around the Urir Char area. This illustrates the texture-based sediment dispersal process in the Meghna Estuary. Dalrymple and Choi (2007) stated that sand-sized sediment becomes finer during its journey towards the sea from the river-dominated area, and becomes finer while they move landward again.

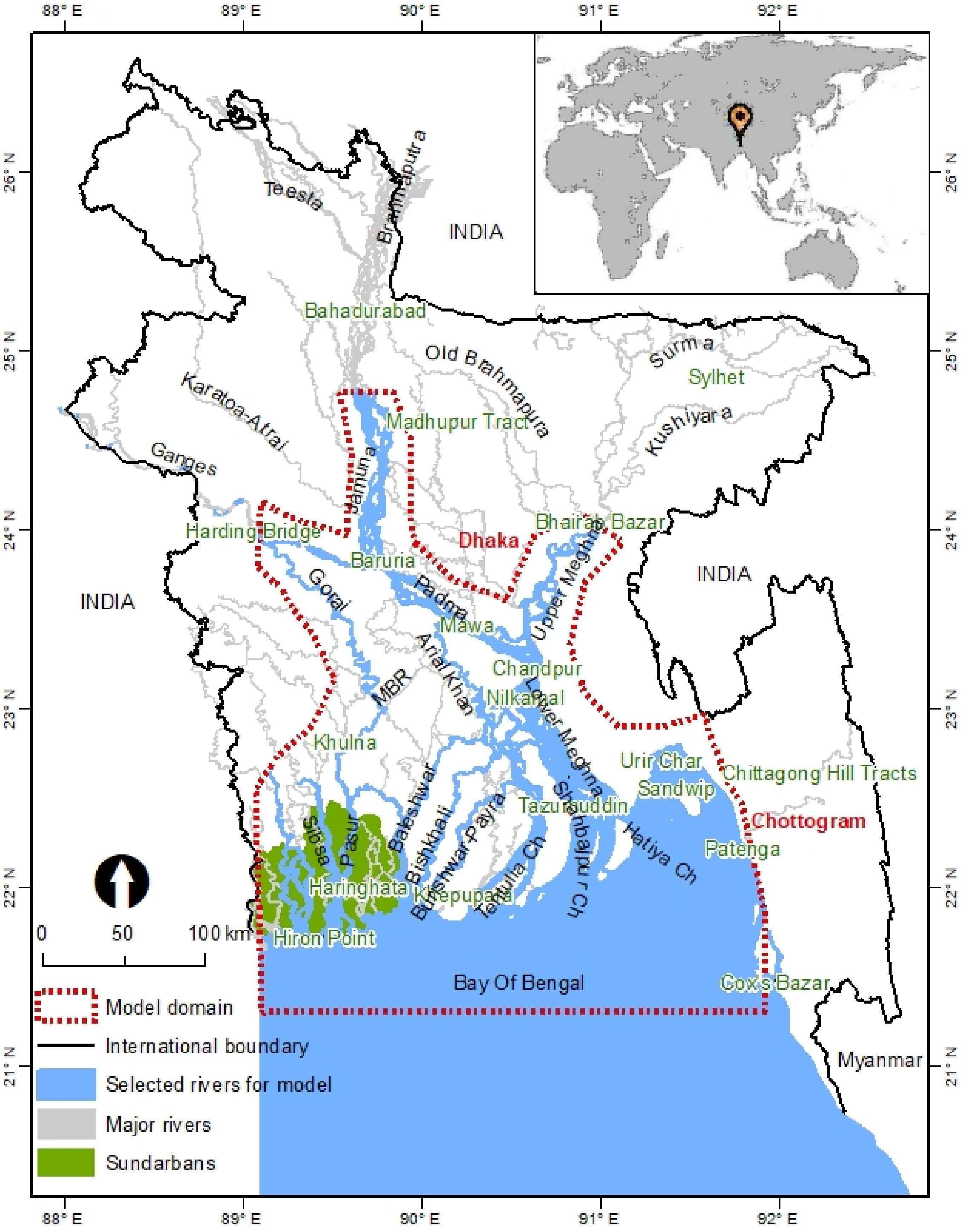


Figure 6.1: The boundary of Bangladesh and the extent of the model domain

Due to the high stream power and large sediment load, the main rivers, the Ganges, Jamuna, and Upper Meghna, are very dynamic. Channel development and abandonment, channel migration, bar movement, and rate of bank erosion are very fast in these rivers. Decadal scale channel migration in the fluvial region through migration and expansion is visible in the major river systems of the model, for example- the Ganges, Jamuna, Upper Meghna, Lower Meghna, Gorai, and Arial Khan rivers. Other important rivers in the south and southwest regions of Bangladesh were not included in the model domain due to the coarse grid of the model.

Significant fluvial sediment supply to the Meghna estuary causes some deposition in the estuary area and the deposition pattern is visible in the central (Meghna estuary area) and eastern (around Urir Char area) parts of the delta. In contrast, the lack of fluvial sediment supplies in the western part of the delta (Pasur-Sibsa estuary area) causes sediment from the sea-side to intrude inside the system. It is a combined effect of river discharge, tides, and waves, as they control estuarine/deltaic morphodynamics mostly (Wright and Coleman, 1972; Galloway et al., 1975; Dalrymple et al., 1992).

In the Padma River, mainly bend and confluence types of scour are observed, whereas, in the Jamuna River, mainly confluence scour is found. The scour at Chandpur is caused by a combination of the protrusion (for Chandpur town protection), the confluence (of the Padma and the Upper Meghna rivers), and bend scours. The scour depth at this location has been increasing since the 1960s (Haskoning, 1992; and IWM, 2005 and 2006).

Maunsell and AECOM (2010) studied the scour-hole process in the Padma River and found a good match for the confluence scour with the available empirical relations of Klaassen and Vermeer (1988) and Thorne and Maynord (1995). The lowest scour level at Mawa was observed to be around -40 m PWD in recent years. The observed scour depth at Chandpur has an increasing trend. Annual flood discharge has no relation with the scour depth development, rather it has a direct relation to the planform development of the Padma River.

6.2 Model Setup

Delft3D is a multidimensional (2-D or 3D) hydrodynamic and sediment transport model that calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a curvilinear, boundary-fitted grid (Lesser et al. 2004, Hibma, 2004, and van der Wegen, et al, 2008). To reduce computational time and resources, a depth-averaged (DH) approach was applied in this study, that is, the governing equations of the same model are integrated over depth. This model solves two-dimensional vertically integrated (2-DH) shallow-water equations coupled with advective-diffusive transport and includes sediment transport formulations for cohesive and non-cohesive sediments. Van Rijn's (1993) formulae are used by default for non-cohesive sand transport and Partheniades-Krone formulae (Partheniades, 1965) were used for calculating the fluxes between the water phase and the bed for cohesive mud.

Working with a large-scale morphological model on a tide-dominated delta is challenging. In addition to the complexity of fluid, wave, and/or tidal processes, data scarcity and data quality for boundary conditions are the main constraints for working in any large-scale delta. So, for preparing the discharge data set and sediment availability in the domain, a 1-D Delft3D model was developed earlier. Then we schematized river flow and sediment input, wave action, and tides. Later on, a 2-D area model was developed. The digital elevation model (DEM) from the National Water Resources Database (NWRD), based on the 1950s agricultural maps of the Bangladesh Water Development Board (BWDB), was used for land elevations. For seabed bathymetry, data generated from the Bangladesh Navy charts of 2010 was used. For river bathymetry, a new approach was adopted and will be discussed in the subsequent section. We assessed model performance in terms of water levels and morphological patterns. In this chapter, we take the opportunity to generate new insights on sediment budgets in the GBM system and to address their pathways within a complex delta system.

All the elevations were considered for Public Works Datum (PWD). PWD is a horizontal datum believed originally to have zero, which is approximately 0.46 m (~1.5 ft) below the mean sea level (MSL) established in Calcutta (India) under the British Rule and brought to Bangladesh during the Great Trigonometric Survey (FFWC, 2014), during early 19th century.

6.2.1 Topography, Grid, and Bathymetry

The model requires an initial bathymetry in the river itself, adjacent floodplains, and the hinterland. Due to lack of data, we have not introduced any levees or dikes, or polder protection in the model, whereas, in reality, the Bangladesh coastal region has featured considerable embankments since the 1950s-70s, with obvious consequences for sedimentation.

To characterize the topography of the hinterland system (except river system and Sundarbans at the southwest part of the delta, the Madhupur Tracts, and the Chittagong Hill Tracts) a set of DEMs was compiled. This DEM with a resolution of 300 m, generated from agricultural maps of the 1950s, was collected from the NWRD. This dataset does not cover river and marine bathymetry. So, for the marine domain, it was adjusted with another set of data, which was generated based on the Navy Chart of 2010 with Geographical Information System (GIS) tools and techniques. Also, for river bathymetry, a new approach was adopted by a 1-D modelling work, where.

River corridor locations were specified based on the last century's floodplain corridor as incised by the rivers. River bed morphology in the GBM deltas changes even on a daily scale, where continuous survey charts or bathymetry data collection is almost impossible for a developing country like Bangladesh. Only the Bangladesh Inland Water Transport Authority (BIWTA) collects river survey charts, mostly on specific river routes for their regular maintenance works. Hence an alternative method was adopted for preparing river bathymetry. As described in the former chapter, a 1-D modelling work generated an initial bathymetry. In this 1-D model, we varied a linearly sloping profile (by slope magnitude and depth at the river mouth) until (scarce) observed hydrodynamic parameters such as tidal amplitude and tidal difference were met. (discussed in an earlier chapter). We then imposed the validated 1-D profile (average slope of 4 cm/km; average river mouth depth of 6 m) into the river corridor bathymetry. The 2-D model would then generate characteristic morphodynamic river meandering patterns like Van der Wegen and Roelvink (2008).

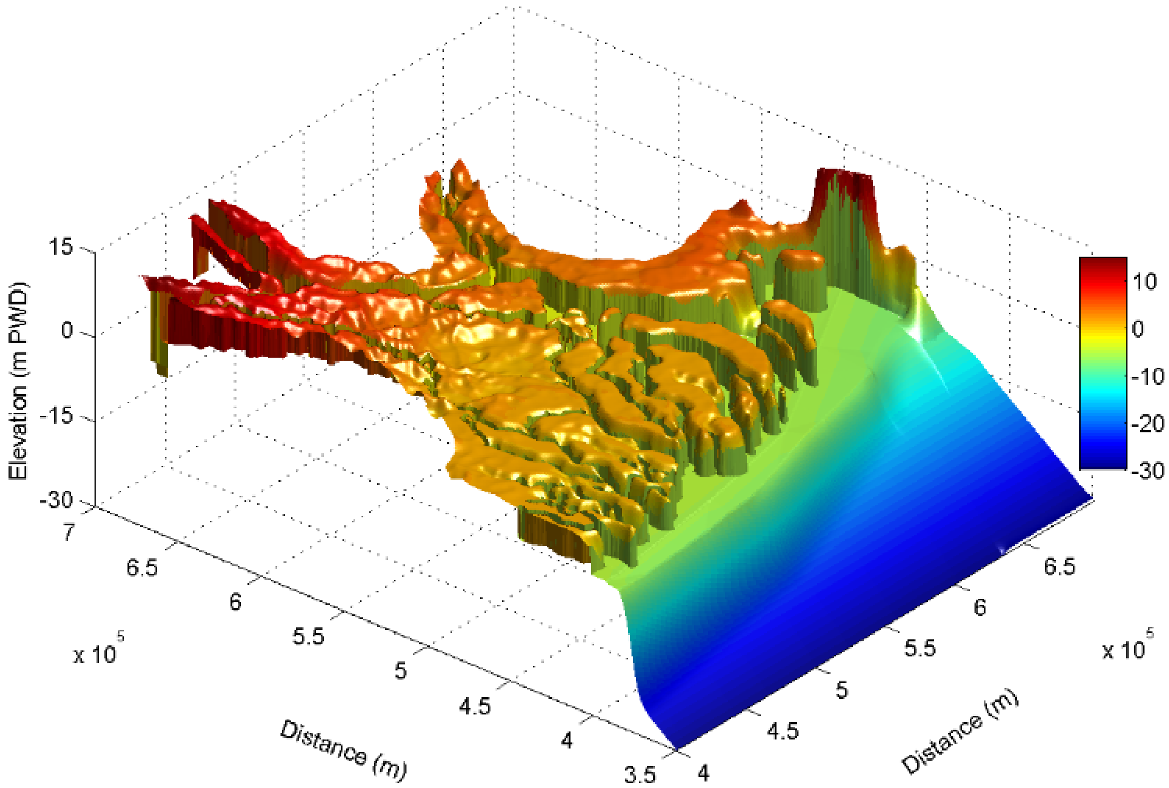


Figure 6.2: Initial topographical and bathymetrical model input

Figure 6.2 shows the initial topographical and bathymetrical data input for the model. The model domain consists of a rectangular basin of 300 km x 350 km with a varying elevation of 15 to -30 mPWD. The model applied a uniform grid of squares. A sensitivity analysis (with

100m, 200m, and 500m rectangular grids) was carried out for selecting grid size. As the morphological changes for different grid sizes were stable and similar, we selected the 500 m grid for optimizing computational resources. The 500 m grid was small enough to resolve the main river branches that have an order of magnitude of 2 to -20 km. Still, the GBM channel network is extremely dense and features many connected distributary channels of scales smaller than 500 m (Passalacqua et al., 2013). The current model does not represent this detailed connectivity. Only major connectivities were considered. A time step of 1 min was imposed to maintain a controlled Courant Number (<10) to assure numerical stability on that grid system.

6.2.2 Morphological River Discharge

Good data input in the model is fundamental to producing good model results, along with a clear understanding of the physical processes. But, is it necessary to put all real data to represent the long-term morphological process? As limited changes occur within an ebb and flood phase in a tidal system (Roelvink, 2006; Roelvink and Reniers, 2011; Guo et al, 2015), an input reduction method (de Vriend et al., 1993; Li, et al., 2017) was carried out. This reduction approach reduces computational efforts significantly. To represent the river discharge variation through the year on the correct morphological timescale, we squeeze the yearly curve into a shorter period, i.e. one year divided by the morphological factor. For testing this input reduction method, we used our 1-D model. as discussed in an earlier chapter. We considered both a dry and flood discharge in the upstream and tides in the downstream boundary. We also used the long-term bed level changes with the help of the morphological factor (MorFac) approach (Roelvink, 2006). This morphological upscaling method is described in a subsequent section.

The 1-D model results show that running the model with a 360-days hydrograph and a MorFac of 1 (total of 360*1=360 morphodynamic days) leads to a similar profile as running the model with a 12-days hydrograph and an MorFac of 30 (total of 12*30 = 360 morphodynamic days). A higher MorFac (>150) leads to less propagation of the deposition front and a slightly higher profile in the rest of the domain. Thus, we use 240 hydrodynamic days (20 times a 12-day hydrograph) with a MorFac of 30, which would represent 20 years morphological period. This input reduction was adopted for optimizing the computational effort by applying a reduced set of forcing (Li, et al., 2017).

The river flow boundary condition was determined based on using a ‘rarely obtained’ (Masood et al., 2015) long-term (1981—2001) observed daily discharge data set provided by the BWDB. We followed the same input reduction process for preparing three long-term river discharge data sets for Hardinge Bridge, Bahadurabad, and Bhairab Bazar for the Ganges, Jamuna, and Upper Meghna rivers respectively. Thus, in total '240 days' of river flow (*.bct) data were applied for the model adding three upstream discharge boundaries. More explicitly, we use a 12-day hydrograph with a MorFac of 30 representing one morphological year.

6.2.3 Sediment Characteristics

Sediment composition has a distinct impact on land and estuary development. Fine particles, i.e. cohesive sediment settle on the land in the floodplain and tidal plain and plays a significant role in the saline zone. Sand particles remain in the riverbeds. Sediment grain size controls settling velocity to the first order. Due to the coagulation/flocculation processes of the cohesive sediments, it has non-linear relationships with the settling velocity. Henceforth, two sediment classes were defined, cohesive mud (median sediment diameter is less than 64 µm) and non-cohesive sand, for the whole domain.

The median diameter of sand is considered to be 0.2 mm, whereas the settling velocity of mud is 0.1 mm/s. The sediment rating curves developed from FAP24 data sets collected during 1993-96 were used for three upstream fluvial boundaries. The relations are shown in **Table 6.1**. Here, the R^2 values indicate how well these rating curves represent the measured sediment transports in kg/s. The density of suspended bed material load and bedload was used for non-cohesive sand load, and the wash load was used for cohesive mud load. **Table 6.2** shows the sediment properties used for this 2-D model.

Table 6.1: Sediment discharge relationships generated from FAP24 datasets

Location	Sediment Loads	Q-S Relationship	UNIT	R^2 values (correlation coefficient)
Bahadurabad (Brahmaputra/ Jamuna)	Wash load	$2x10^{-08}Q^{1.7693}$	Million Ton/day	0.965
	Suspended bed material load	$2x10^{-10}Q^{2.0725}$		0.9026
	Bedload	$6x10^{-14}Q^{2.6252}$		0.9679

Location	Sediment Loads	Q-S Relationship	UNIT	R^2 values (correlation coefficient)
Hardinge Bridge **(Ganges)**	Wash load	$2x10^{-09}Q^{2.096}$		0.9882
	Suspended bed material load	$3x10^{-12}Q^{2.5193}$		0.9413
	Bedload	$5x10^{-14}Q^{2.4602}$		0.8444
Bhairab Bazar **(Upper Meghna)**	Wash load	89.75*lnQ-628.6	kg/s	-
	Suspended bed material load	199.8*lnQ-1471		-

In the downstream boundary of the model, no sediment input was defined, as there was no data available in that part and the area was not of our interest. For increasing the transport capacity of cohesive sediment (mud), we decreased the critical bed shear stress for erosion (Li, et al., 2017).

6.2.4 Bed Roughness

A model functionality, named trachytope, allows us to specify the roughness and flow resistance on a sub-grid level by defining and using various land use or roughness classes in the Delft3d-Flow module. Simple type with constant Chezy's value (**Table 6.2**) for bed roughness in the tidal plain and flood plains was used, whereas for bedforms quadratic equation 105 (see Delft3D Manual) was used for the riverbed. This alluvial trachytopes formula is based on Van Rijn (2007) which assesses the alluvial roughness predictor. The roughness heights are based on Van Rijn's (2007) transport formulae (Delft3D Flow User Manual). According to the equation 105 definitions, the alluvial roughness predictor (*k*) is defined as eq (1).

$$k_s = \min\left(\sqrt{k_{s,r}^2 + k_{s,mr}^2 + k_{s,d}^2}\ , \frac{h}{2}\right) \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \text{eq (1)}$$

According to Van Rijn (2007), the geometrical equivalent roughness for ripples ($k_{s,r}$), mega-ripples ($k_{s,mr}$), and dunes ($k_{s,d}$) are the basis of predicting a bed roughness. The k_s value is then used in the suspended sediment transport formula to calculate the bed shear stress. The bed roughness varies, in reality, at all times and at all points in space, according to sediment grain size, water depth, and flow velocity.

6.2.5 Sediment Availability in the Domain

Preliminary 2-D model results show that with the increase of sand availability in the domain, the river becomes more dynamic and shallower. On the other hand, when the mud fraction increases the river deepens and narrows. Sand only would reproduce the most realistic channel-shoal patterns, but transport volumes would be far too low when considering only sand. However, we have done a few simulations considering sand or mud availability in the domain. Finally, we have assumed 50 m sand availability in the riverine domain (floodplain, tidal plains, and rivers system), whereas no sand is available in the marine domain. Only sand and mud will come to the domain from the upstream three boundaries at Hardinge Bridge, Bahadurabad, and Bhairab Bazar.

6.2.6 Morphological Tides

A complex time series of tidal water levels and induced currents can be schematized by a simple "morphological tide". This concept states that a representative morphological tide has a similar net effect on the residual sediment transport and morphological change, as compared to simulating sediment transport associated with complete high time resolution tidal dynamics (eg a spring-neap tidal cycle). The morphological tide is specified based on Latteux (1995) and Lesser (2009). For his particular case study on the US West Coast, the morphological tide is considered to have a 7-20% larger amplitude than the largest constituent "principal lunar semi-diurnal" M2 tide by Lesser (2009). An artificial diurnal component ($C1 = sqrt(2O_1K_1)$ and $\varphi C1 = (\varphi O1 + \varphi K1)/2$) is added to the M2 tide to represent the morphological tide. Lesser (2009) has suggested the amplitude and phase of the C1 tide as a function of diurnal components (O1 and K1), where these two diurnal tides are considered to be important for the morphological simulation. Therefore, a combination of M2 and C1 tides at sea boundary was used for this study. As a result, tidal forcing consisted of a daily varying tidal signal that is constant during a model run.

6.2.7 Seasonal Variation of Mean Sea Level

As found from the 1-D modelling exercise, seasonal water level variation at the downstream boundary is an important factor. As the tidal wave approaches the coastal areas of Bangladesh, it is affected at least by four factors causing amplification and deformation of the wave: Coriolis' acceleration, the width of the transitional continental shelf, the coastal geometry, and the frictional effects. Similarly, analysis of the tidal water level at Cox's Bazar, Potenga, Chittagong, Sandwip, and Hiron Point shows that the seasonal mean tide level variation varies between 0.5 m and 0.9 mPWD. Hence, a seasonal variation of mean water level at the sea boundary is adopted to have a 0.35 m amplitude, resulting in a seasonal variation of 0.7 m in the deep sea.

6.2.8 Morphological Up-scaling Methods

After setting up the topography and bathymetry of the GBM system along with morphological discharge and tides for the 2-D model, a method for accelerating the morphodynamic evolution relative to the hydrodynamic time scales using the Morphological Acceleration Factor (MorFac) (Lesser et al., 2004), defined by Roelvink (2006), was adopted. This MorFac approach is bridging the gap between small-scale hydrodynamic and transport processes and large-scale morphological changes in long-term modelling (Roelvink, 2006). By this method, bed levels are updated multiplying by the MorFac. However, the high value of MorFac would typically lead to numerical instabilities with an unrealistic morphological evolution (Li, et al., 2017; Ranasinghe et al., 2011).

Li, et al. (2017) also found that the application of acceleration methods does not significantly affect the simulated delta evolution if the variability of the accelerated models falls within the 'autogenic variability range'. Li, et.al. (2017) found that the autogenic variability for the delta is small, as it is mainly controlled by the fluvial sediment without changing its accommodation space.

Rerunning the identical models with the same sets of data, a series of MorFac values (30, 60, 120, 150, 240, and 480 considering MorFac of 30 used for morphological discharge), were used for comparing the morphological response on the system. The results showed that until using MorFac 30 to 150, the morphological changes (volume changes over time) do not differ significantly. Hence, for reducing the computational efforts and times, the 2-D GBM delta model was accelerated by a MorFac of 150, considering morphological discharge. Thus, the model runs for 240 hydrodynamic days, which in turn computed the morphological changes for 100 years with a MorFac of 150.

6.2.9 Wave Impact

Kowser et al. (2014) measured the significant wave height of the BoB during 2010, 2011, 2012, and 2013. Significant wave height is generally variable, but the pattern is systematically similar from April to October and fluctuates between 0.5 to 1.2 m from November to March. They found a range of wave height from 0.8 m to 1.8 m, whereas the wave period range was 6 sec to 11 sec. Hence an averaged wave condition with 1.2 m for 8 sec from 180^0 (south boundary orientation) was considered for our model. The wave grid for the model was considered coarser (1.5 km) than that of the flow grid (500 m) to avoid any unrealistic morphological development, especially at the end of all bars in the estuaries. We did not consider storm surges.

6.2.10 Other Model Parameters and Setting

A detailed description of the model inputs is given in **Table 6.2** for the reproducibility of the experiments.

Table 6.2: List of modelling parameters and setting

Parameters (unit)	**Value**
Chezy’s roughness	100
Horizontal eddy viscosity (m^2/s)	1
Horizontal eddy diffusivity (m^2/s)	10
Settling velocity of mud (mm/s)	0.1
Median diameter of sand (µm)	200
Dry bed density for sand (kg/m^3)	1600
Dry bed density for mud (kg/m^3)	800

Parameters (unit)	**Value**
Critical bed shear stress for sedimentation (N/m^2)	1000
Critical bed shear stress for erosion (N/m^2)	0.1
Factor for erosion of adjacent dry cells	1
Spin-up interval before morphological changes (min)	720
Erosion parameter (kg/m^2/s)	0.0005
Thatcher-Harleman time lag (min)	360
Reflection parameter alpha	1000
Depth switch wet-slope to dry-slope for avalanching	0.01 (5 m depth in 500 m grid)
Transverse bed gradient factor for bedload transport	1000
Stream-wise bed gradient factor for bedload transport	500

Note that the high transverse and stream-wise bed gradient factors are applied to avoid narrow and steeply incised channels, an artefact of the model caused by the simple representation of sediment properties and the low spatial resolution.

This model was run on a supercomputer with the high-performance computing (HPC) Cloud facilities offered by SURFSara to the Dutch academic community. Each simulation took more than a month.

6.3. Model Results

6.3.1 Hydrodynamic Validation

Water level data were used for validating the model in the hydrological aspect. Secondary data, spring and neap tidal range as a function of distance, generated from water level data, were also compared with the observed data set.

We computed hydrodynamic conditions in the fluvial and coastal environments, where tides and waves have a potential influence on morphological development. The model was validated hydrodynamically in both fluvial and coastal environments. The model was run on a fixed bed following slopes derived by the 1-D model. Observed water levels data at Mawa (approximately 165 km upstream from the river mouth), Chandpur (120 km upstream), Nilkamal (105 km upstream), and Tazumuddin (20 km upstream) were prepared for a comparison with the computed data. Water levels of July-September and February-April were considered flood and dry seasons respectively.

Figure 6.3 (top) shows the comparison between computed and observed seasonal (dry and flood seasons) water levels at those four selected stations. Computed seasonal water levels at Tazumuddin seem to be a good match with the observed water level. However, water levels at Nilkamal and Chandpur are slightly under-estimated. Flood season water level at Mawa shows a little under-estimation, whereas that of the dry season shows some over-estimation. The results indicate that most of the model results are close to the measurements.

Another comparison was made based on the mean tidal range during a spring-neap tidal cycle of 15 days for those four monitoring stations. The tidal ranges at those locations based on the distance from the river mouth at Tazumuddin are shown in **Figure 6.3** (bottom). For verification of the effect of the river discharges on tidal propagation, the monsoon month of September and the dry month of April were selected.

The dry and flood season tidal ranges at Tazumuddin were observed as 2.63 and 2.08 m, whereas 2.7 and 1.9 m tidal ranges were computed from the model results respectively. At Nilkamal, observed tidal ranges during the flood and dry seasons were 1.06 and 1.08 m respectively, while computed tidal ranges are 1.2 m for both periods. At Chandpur, the confluence of the Upper Meghna and Padma rivers, the tidal ranges were monitored as 0.68 and 0.81 m, and model results were indicated as 0.75 and 0.85 m for those flood and dry periods respectively. The tidal ranges were almost ended at the confluence of the Jamuna and Ganges rivers, at Baruria Transit, with 0.03 and 0.06 m, while the model generated results show no difference in the two different periods. In the model, tides were ended around Baruria, whereas in reality some tidal variation is observed further upstream. But tidal attenuation along the system was captured by this 2-D model.

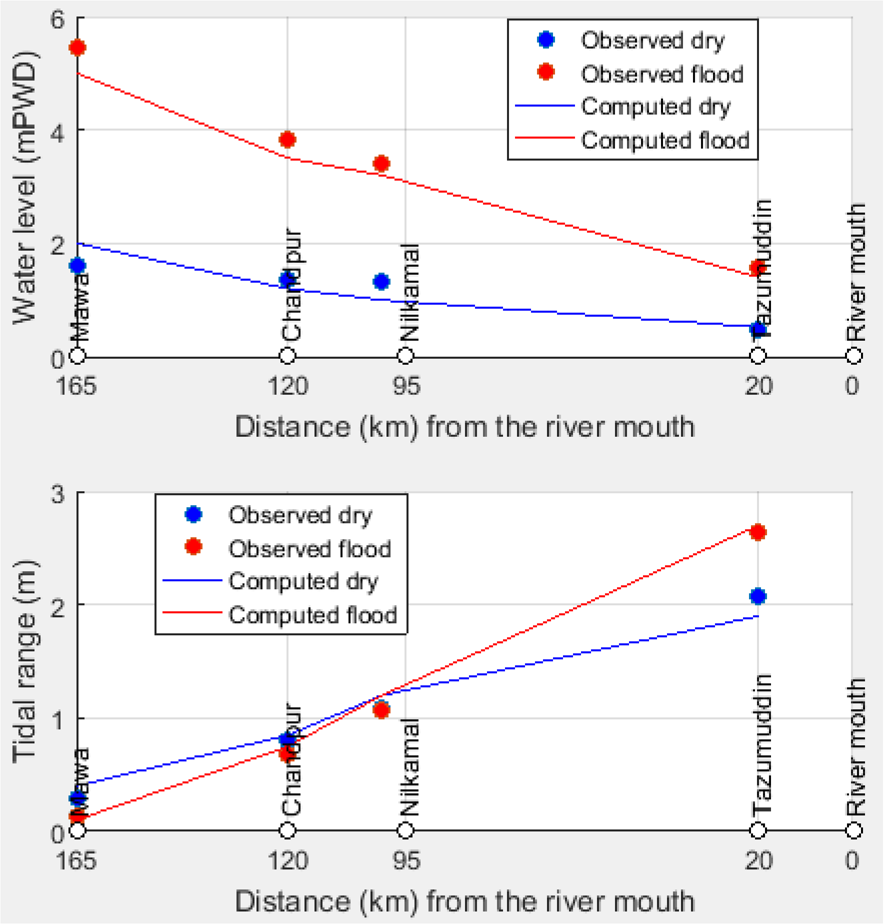


Figure 6.3: Comparison between the measured and observed seasonal water level (top) and tidal range (bottom) at four locations in the Padma and Lower Meghna rivers as a function of distance

6.3.2 Morphological Validation

We use morphological patterns and trends from satellite images and observations to assess the decadal-scale morphological model result as suggested by de Vriend, et. al. (1993).

6.3.2.1. Channel Migration, Formation

Figure 6.4 shows the bed level changes (right panel) after 100 morphological years from its initial delta (left panel) with fluvial and marine forcing. After filling up the accommodation space in the rivers' confluences (especially confluences of Jamuna and Ganges, and the Padma and Upper Meghna) in the initial period after model running, mouth bars were developed and those bars were reforming later on. In the marine domain, the delta was found to be developed following the tidal circulation process. But we had to remove the SNG for model stability and hence we could not address the effect of its presence in the model domain.

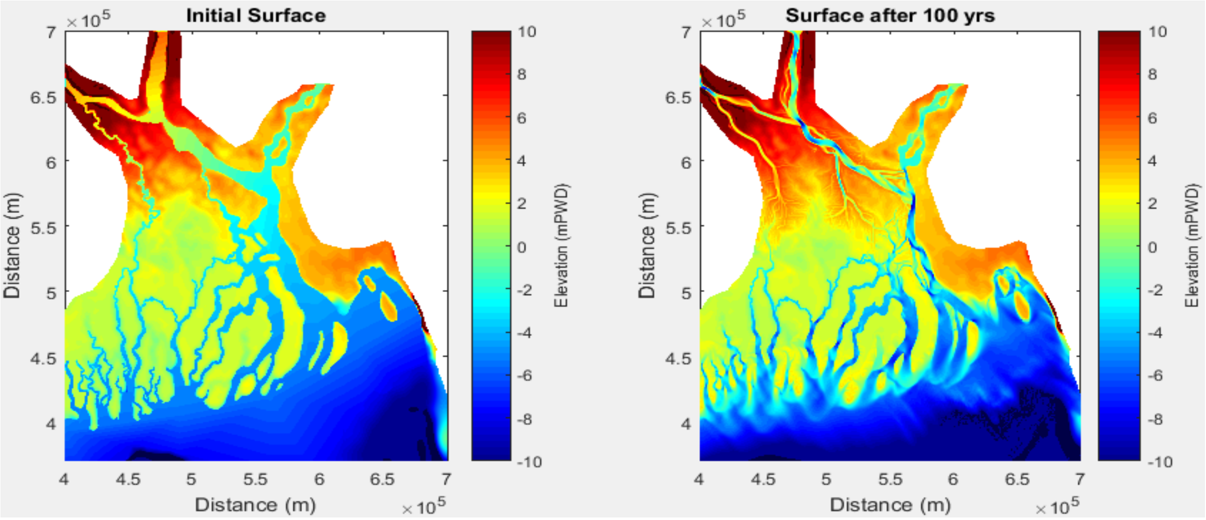


Figure 6.4: Delta development after 100 morphological years

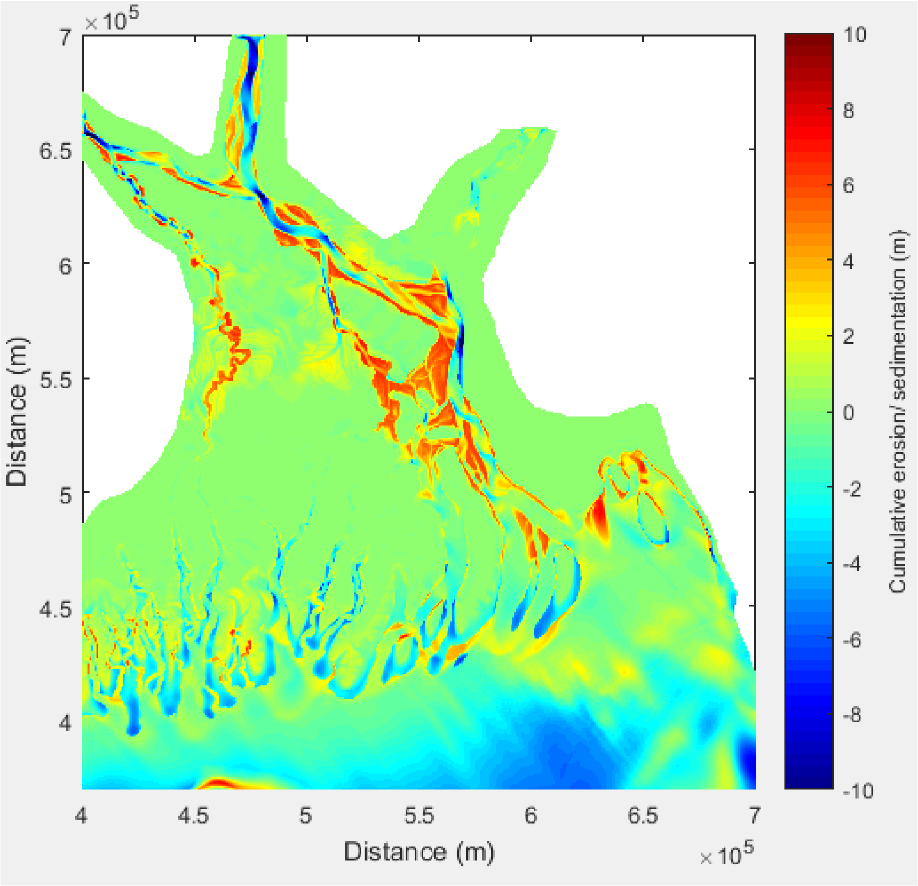


Figure 6.5: Cumulative erosion/ sedimentation after 100 morphological years

Figure 6.5 shows the cumulative erosion and sedimentation during 100 morphological years. The evolution patterns of the modeled domain were highly variable in the beginning, but later the evolution process slowed down and it was not in equilibrium till the end of the simulation period. There was a pulse of evolution during every monsoon. From Figure 6.5, the land development/adjustment is indicated at and around the river boundary. It shows the land development process is active in the Padma-Lower Meghna River System. It is also active along the Arial Khan River floodplains. Land development in the Urir Char area (north-east tip of the bay) is quite matching with reality during the last few decades.

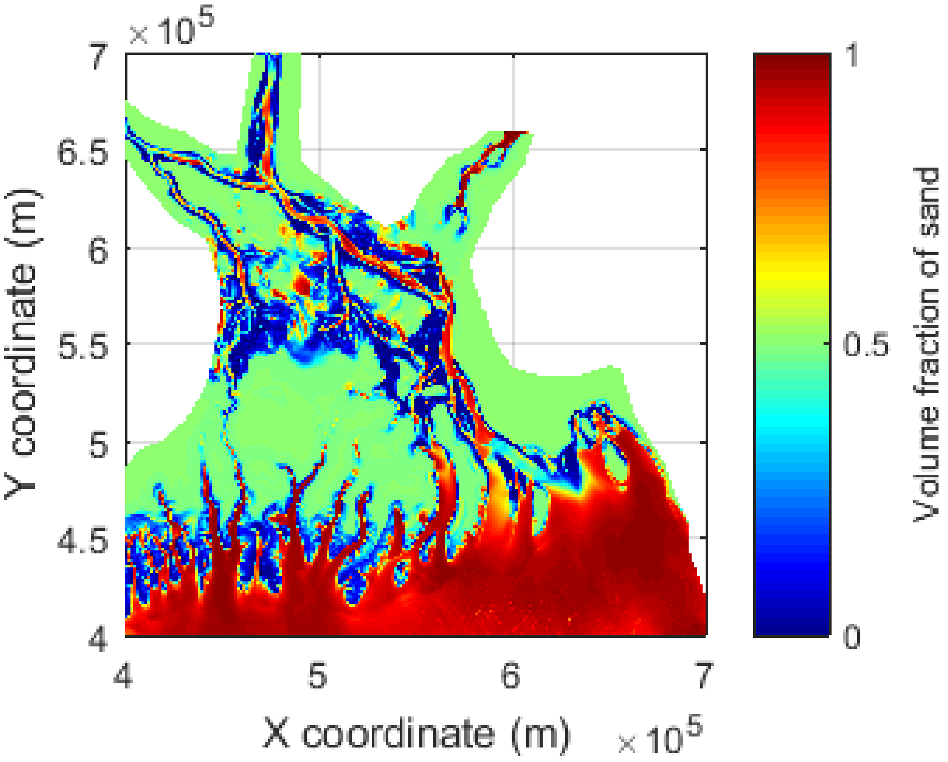


Figure 6.6: Sand /mud ratio after 100 morphological years

Figure 6.6 shows the distribution of the sand (red colors) and mud (blue colors) in the model domain during the simulation period. Mostly sand distribution was in the riverbed and sea bed, whereas mud deposition is noticeable in the river floodplain. Mud deposition in the central part of the system, in the Beel area, is also clearly visible. Significant mud deposition in the western coastal areas indirectly supports the presence of the mangrove forest.

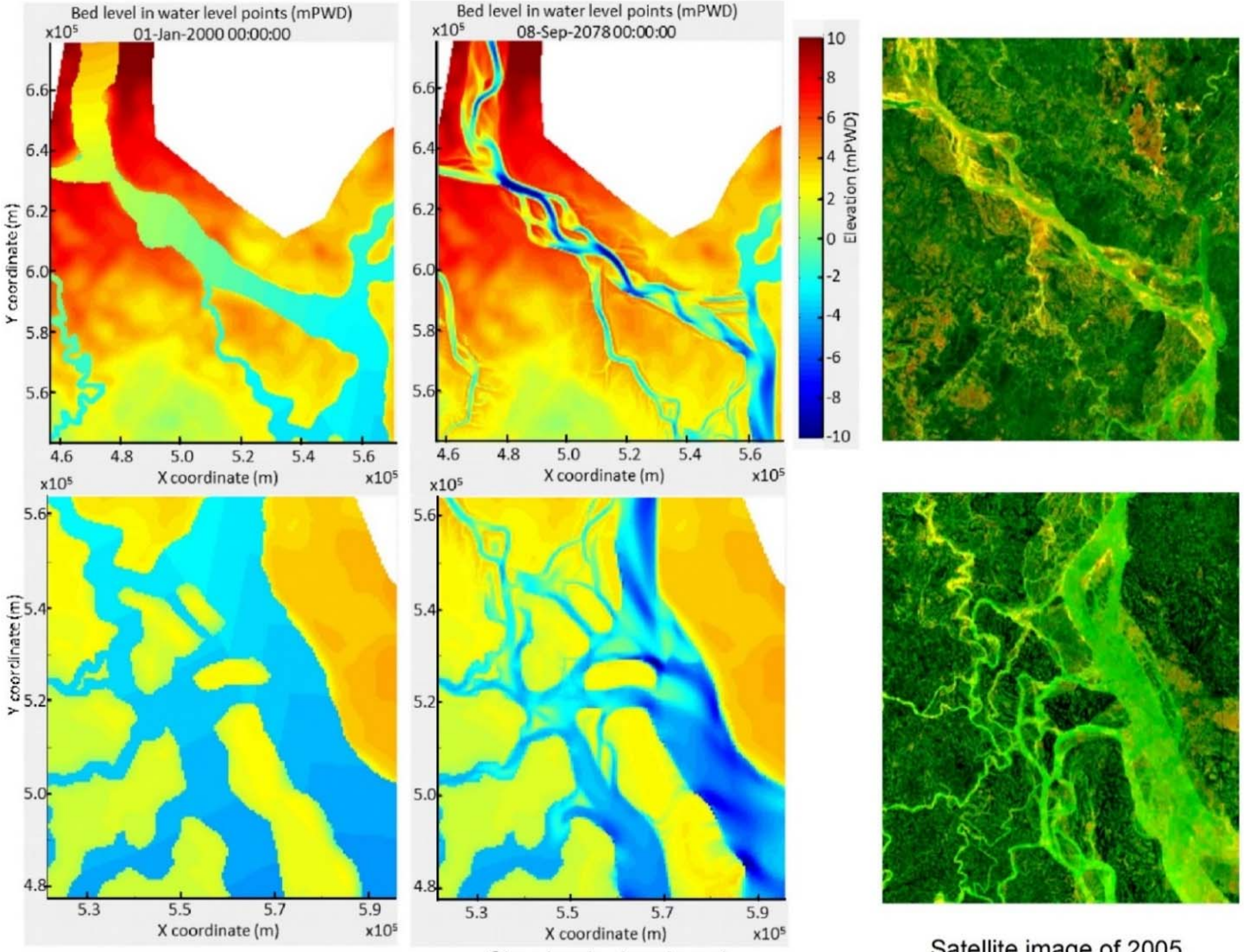
Sand distribution from south of Bhola and Patuakhali districts, where the delta is presently active, slows down to the east. In the same line, the maximum fraction of sand is observed in the south of Bhola and minimum at and around the Urir Char area. This illustrates the texture-based sediment dispersal process in the Meghna Estuary. Dalrymple and Choi (2007) stated that sand-sized sediment becomes finer during its journey towards the sea from the river-dominated area, and becomes finer while they move landward again.

6.3.2.2. Channel migration, formation, and abandonment

Due to the high stream power and large sediment load, the main rivers, the Ganges, Jamuna, and Upper Meghna, are very dynamic. Channel development and abandonment, channel migration, bar movement, and rate of bank erosion are very fast in these rivers. Decadal scale channel migration in the fluvial region through migration and expansion are visible in the major river systems of the model, for example- Ganges, Jamuna, Upper Meghna, Lower Meghna, Gorai, and Arial Khan rivers. Other important rivers in the south and southwest regions of Bangladesh were not included in the model domain due to the coarse grid of the model. **Figure 6.7** shows the bed level changes after 100 morphological years from its initial delta with fluvial and marine forcing. After filling up the accommodation space in the rivers' confluences (especially confluences of Jamuna and Ganges, and the Padma and Upper Meghna) in the initial period after model running, mouth bars were developed and those bars were reforming later on. In the marine domain, the delta was found to be developed following the tidal circulation process. Decadal-scale delta development in the marine parts is visible. As the model is not in an equilibrium state, the development process is still high.

6.3.2.2 Char/Island Development in the Fluvial Region

The model was able to create the char lands in the GBM rivers (**Figure 6.7**). Due to the coarse grid, it could not reproduce small islands in the other parts of the fluvial regions. These types of features play an important role in the river and estuarine morphology. They control channel migration to river avulsion to channel abandonment. They are broadly responsible for guiding the river flow and sedimentation in the riverbed to riverbank erosion. The model reproduced a very similar pattern. Using a finer grid with long-term simulation, the pattern of planform evolution is expected to be reproduced with more efficiency. However, in this model result, the planform patterns of the Padma and Lower Meghna and the island development are found to be very similar to the observed patterns of the satellite image of 2005.



Initial Bathymetry

Char lands developed by the model

Satellite image of 2005
Source: Google Earth

Figure 6.7: Computed Char lands and comparison with the satellite images of 2005

6.3.2.3 Shoal Development in the Tidal Region

The model results reproduce the evolution pattern of the GBM estuaries with progressive seaward propagation of shoals, tidal flats fringing the western side, successive filling in the north-east side of the BoB (around Urir Char area), a resultant seaward migration of the river mouth. Gradual channels and shoals adjustments occur by downward river-borne sediment flushing. In the last few decades, due to the more stable coastline for establishing coastal embankment, the overall large-scale channel-shoal patterns are stable. Still, the breaking of the embankment also happens resulting from high forces in the channel. Continuous small-scale erosion and deposition are occurring outside the embankment and in unprotected shoals, especially in the marine domain that is sea exposed.

6.3.2.4 Hypsometry changes

The interaction between water and sediment flow and bed topography fixes the estuarine morphology (Hibma et al, 2004). The macro-scale shape of estuaries is associated with the influence of waves and tide. Friedrichs and Aubrey (1996) developed a model that correlates these forces with the hypsometry of basins. Hypsometry is the distribution of horizontal surface area to elevation. Hypsometry is popularly used as an indicator of the geomorphic form of catchments and landforms (Willgoose & Hancock, 1998; Schumm, 1956; Strahler, 1964). In the hypsometry of the whole area used for this particular work, as shown in **Figure 6.8**, the upper part of the hypsometry (>7x10^4 sqkm) has a fan delta slope (≈10^{-4}) displaying a concave shape where fluvial delta plain (3.7x10^4 sqkm to <7x10^4 sqkm) slope is less than 10^{-5} revealing low-land. The topography downstream of the fan-delta regions smooths and explains the low-lying fluvial tidal delta plain (Wilson and Goodbred, 2015).

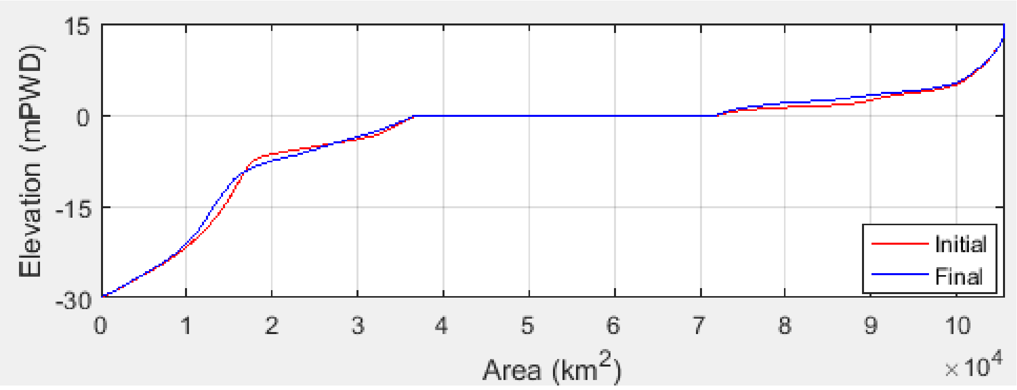


Figure 6.8: Hypsometry changes over 100 years for the whole domain

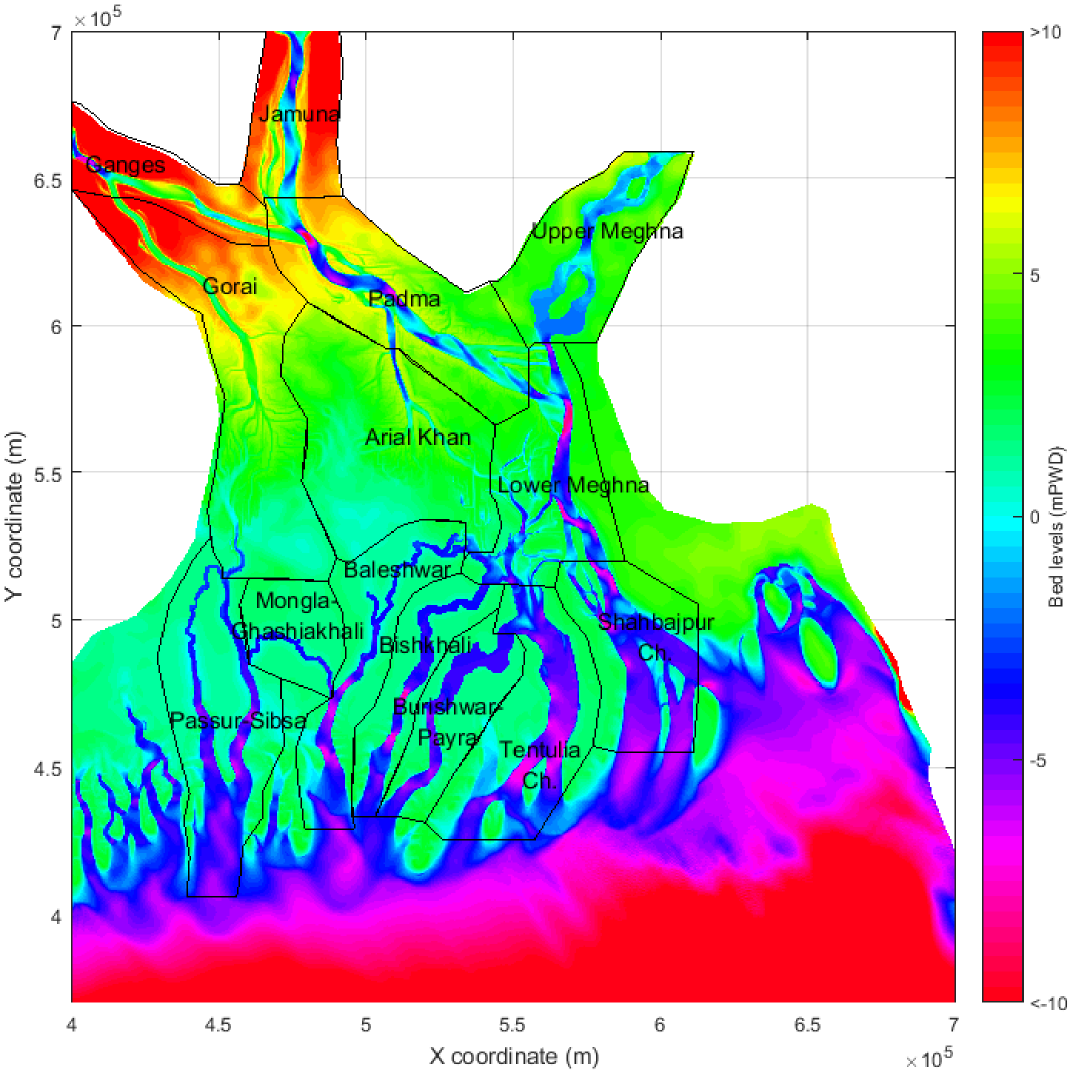


Figure 6.9: River systems in the domain

Hypsometry results show that there are no land level changes in one-third (3.7-7.2 x10^4 sqkm) of the total area (**Figure 6.8**). It indicates the non-accessibility of the rivers in the tidal plain since the repeated schematized discharge variation misses the higher peak discharges. Due to the usage of the coarse grid (500 m), it was not possible to reproduce any sedimentation in the riverbanks. Most of the river widths in the coastal regions are less than 500 m. The land level (elevation >0 m) of a substantial portion of the area is found to be increased, indicating that the delta plain sedimentation is active in the Lower Meghna Estuary, whereas the bed level of few areas (elevation < 0m) are found to be eroded. Due to the active building process, land development occurred on the right bank of the Lower Meghna River, and in the floodplains among the Gorai, Padma, Arial Khan rivers. **Figure 6.9** shows the river systems in the domain that are considered for further detailed analysis. **Figure 6.10** shows the system-wise (controlled, based on river system as described in **Figure 6.9**) hypsometry changes over 100 morphological years.

A Hypsometric Index (HI) of a basin, often called the elevation/relief ratio, is a general indicator of basin's relief, i.e. erosional development. The HI can be obtained by, HI = (Lavg – Lmin) / (Lmax – Lmin); where Lavg = Mean elevation value (not median), Lmax = Maximum Depth of Channels elevation value, and Lmin = Minimum elevation value (outlet). HI can be interpreted as the mean incision of a basin (Lavg – Lmin) divided by the basin's relief (Lmax – Lmin). It is a useful geological parameter for comparing several basins to each other. Following **Figure 6.11** shows the HI for all systems.

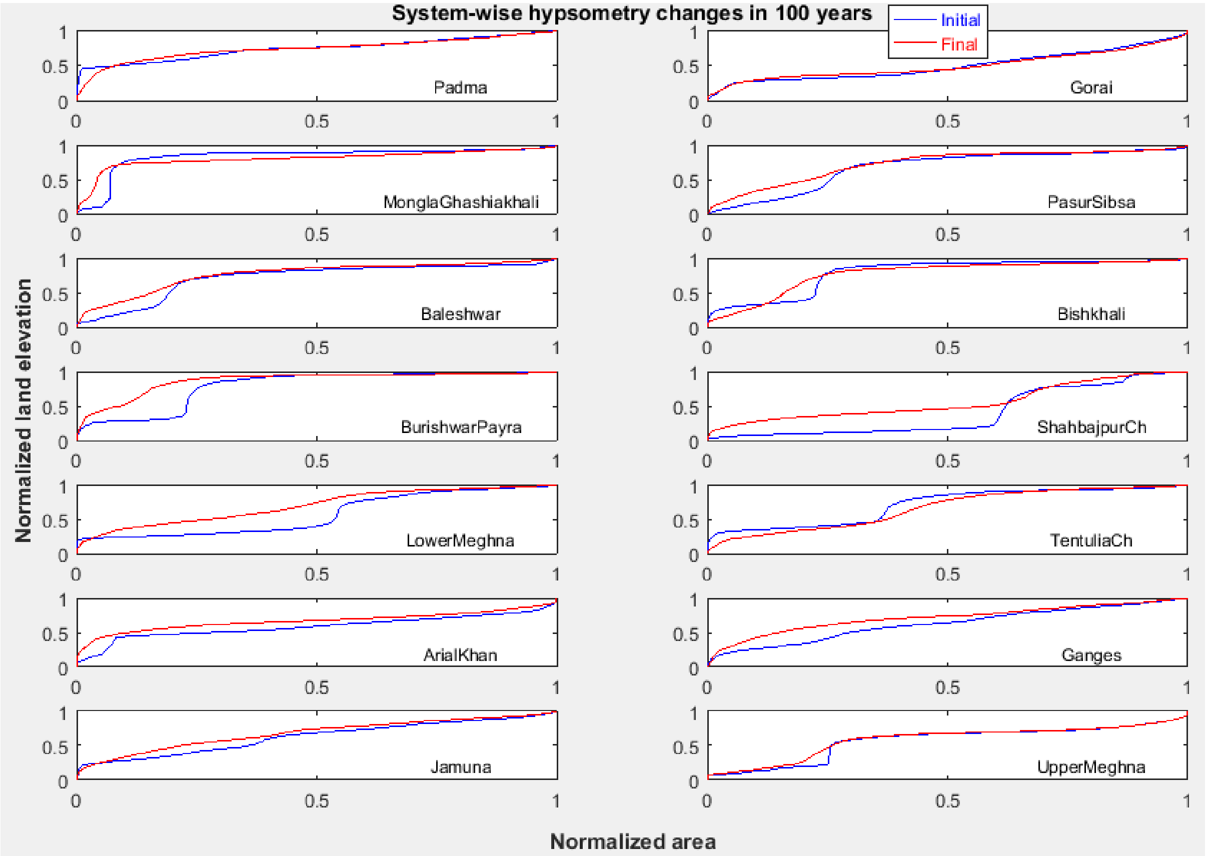


Figure 6.10: System-wise hypsometry changes over 100 years

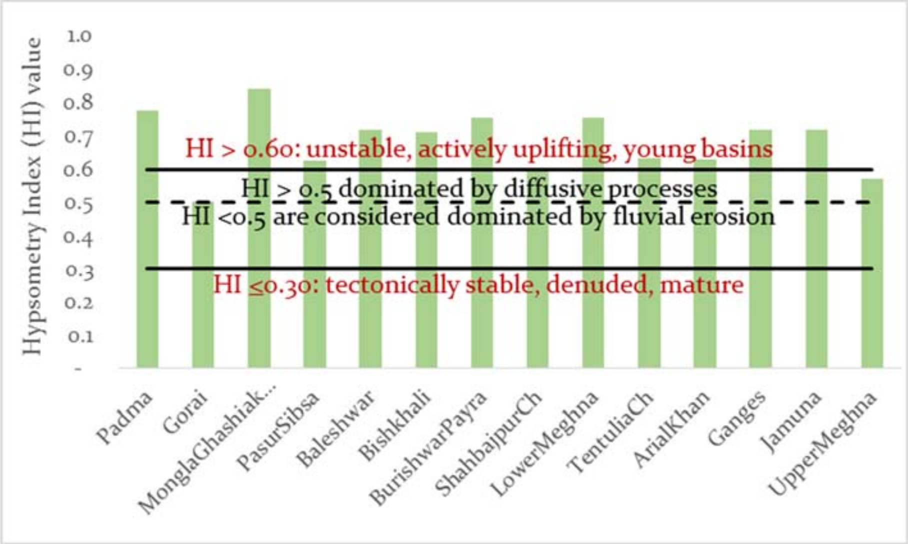


Figure 6.11: Hypsometry indexes of the systems, translated from Figure 6.8

The cycle of erosion was conceptualized by William Morris Davis in the late 19th century. He defined basins with HI values of ≤0.30 as tectonically stable, denuded, and mature; whereas values ≥0.60 as unstable, actively uplifting, young basins. Willgoose & Hancock (1998) interpreted HI value differently. They consider HI values >0.5 governed by diffusive procedures (mainly hillslope processes) and values <0.5 governed by fluvial erosion (channel processes play an important role). Relatively stable with the continued developing landscape would have a more adjusted, straight, or HI value of (~) 0.50. **Figure 6.11** shows the hypsometry indexes of the systems and is categorized based on the definitions made by Davis and Willgoose & Hancock. Based on the definition by Willgoose & Hancock (1998), all the systems within GBM basins are dominated by diffusive processes, except the Gorai system. The HI value of the Gorai system indicates that the system is more adjusted and stable. Based on the definition by Davis, all systems, but Gorai and Upper Meghna, are unstable and young. Because Gorai is a part of the moribund delta and Upper Meghna is a part of the morphologically inert system, the Upper Meghna System was developed for flowing the Brahmaputra River.

6.3.2.6. Maximum depth of channels/ Scour Holes

Scour is the lowering of the riverbed that may occur naturally or may be structure induced or combinations of these two. As the grid size of the model is 500 m, scour depth was found using wet slope which is a flag for underwater critical bed slope avalanching (Roelvink et al, 2009). It was introduced for the slumping of sandy bed material during storm-induced dune erosion for updating bed changes. After sensitivity analysis with changing wet slope values, we have found 0.01 (5 m in 500 m grid) is suitable for the Bangladesh model.

There could be a single or a combination of many reasons for not achieving maximum depth in the model. The use of a relatively low avalanching slope given the coarse grid is one reason. Another could be due to using trachytopes in the model, where it creates bedforms before making any scour. Uses of Chezy's value could be higher in some regions that create low friction. Non-inclusion of structures or incorporation of cohesive sediment at the riverbank in the model might have refrained from developing any sort of protrusion scour. Moreover, sediment availability in the bottom layer could have a great influence on scouring development. Last but not the least, the deepest location would be a sub-grid feature that is not covered by the model grid used for this research.

6.4. Discussion

6.4.1. Annual Sediment Load

The delta is mainly controlled by fluvial sediment coming from upstream river boundaries and autogenic processes. This process includes erosion from a riverbed or marine bed and abrasion from the floodplain and tidal plains. Total incoming sediment loads per year entering the delta system were determined by summing up sediment loads from Harding Bridge, Bahadurabad, and Bhairab Bazar (**Figure 6.12**, top panel). On the other hand, the outgoing sediment load was calculated by summing up all sediment loads going out from the system through the estuary. Then, the storage in the system was calculated after deducting the sediment going out from the sediment coming into the system. The trapping efficiency of the whole system is shown in **Figure 6.12** (middle panel). All these changes of sediment load occur due to irregular discharge data input at upstream boundaries, (**Figure 6.12,** bottom panel).

Much research during the 1960s has already mentioned the sediment load in the GBM system, but those are more than a half-century back. Holeman (1968) suggested sediment load in the Ganges and Brahmaputra Rivers were 1.6 (based on data from 1874 to 1879) and 0.8 (nothing mentioned about the year) billion ton/year respectively. Later, Coleman (1969) estimated sediment load in the Ganges and Brahmaputra was 1.1 billion ton/year, which is less than half of the estimation of Holeman (2.4 billion ton/year). Although, Schumm (1971) agreed that reliable data on sediment transport all over the world is rare. However, the annual average sediment load measured during 1966-1969 by the BWDB indicated that both the Jamuna and the Ganges transport 1050 million ton/year. All these values for sediment loads are considered when a huge landmass was generated by the 1950 Assam Earthquake in Assam (Sarker et al., 2011).

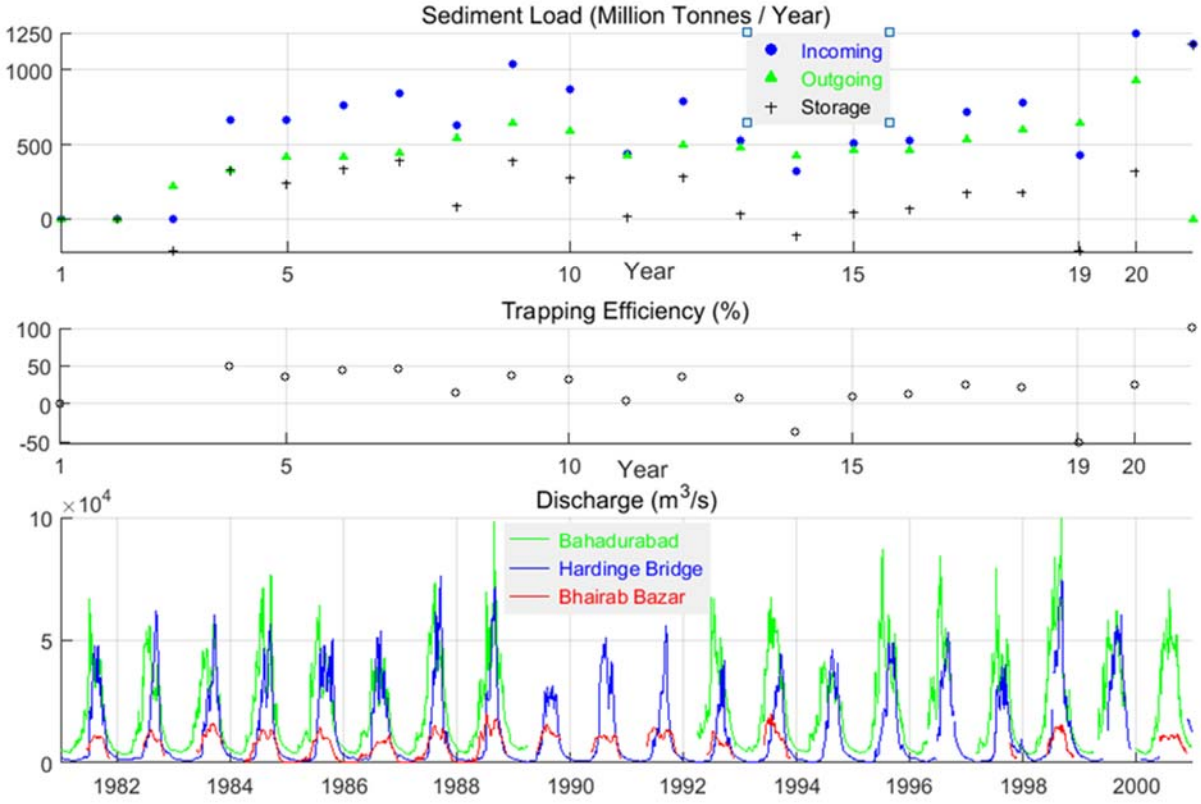


Figure 6.12: Annual variation of sediment loads (million ton/year)

Besides, starting the construction of the Farakka Barrage in India has reduced water and sediment flow in the Ganges drastically. Hence those numerical values may not be any more valid for the system. Recent research by Islam, et. al. (1999) mentioned a wide range of sediment loads in the Ganges and Brahmaputra systems. They suspected the reason for that wide variation is due to seasonal and inter-annual variations along with spatial variability. The mean annual suspended sediment loads for the Ganges and Brahmaputra rivers were 316 and 721 million tons/year respectively based on sediment-discharge rating curves, although the water discharge and sediment discharge had a ‘weak’ relationship. All of those works did not provide sufficient information to reproduce the sediment load. We add the reason for supporting to have lower sediment loads in the systems is attributed to the sediment trap (dam construction) in the upstream regime and less sediment borne in the catchment (land management).

However, from our model results, the sediment loads in the Ganges and Jamuna rivers are found to be in ranges of 216-1038 million ton/year and 80-228 million ton/year respectively.

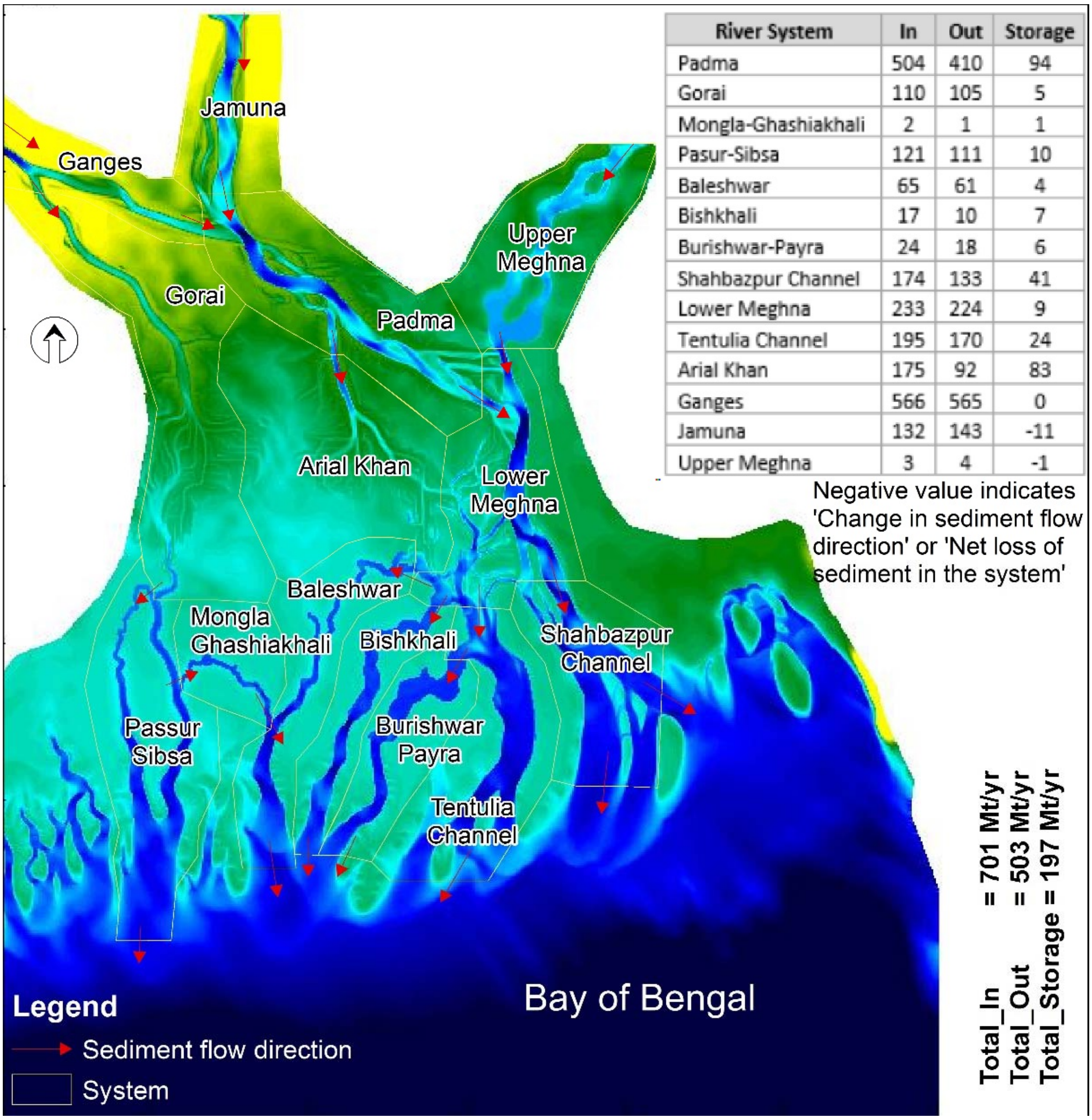
Figure 6.12 (middle panel) shows the trapping efficiency of the total system. This trapping efficiency of the system is defined as a ratio of the quantity of deposited sediment to the total sediment inflow. Negative efficiency indicates an erosional phase of the system. Changes in water and sediment inflows are the main factors for irregular trapping efficiency. Estimations show that the system is mostly in the accretion phase and the trapping efficiency is positive.

6.4.2. Long-term Sediment Budget

Mud transport was found an order of magnitude higher than sand transport. High sediment transport occurred during the wet period that has a high deposition pulse through the model domain. The distributaries and channels in this delta system are dominated by seaward advection due to gravity, although tidal dispersion and sediment settling also occur in the marine domain. The western part of the delta that is a part of the moribund delta, is more than 200 km away from the active river mouth and was found not receiving any fluvial sediment. Tides propagate more than 100 km inland and develop a flood-dominant environment with a net onshore advection of suspended sediment (Allison & Kepple 2001, Rogers et al. 2013). Although, several thousand years ago, this western part was originally developed by the main river system (Alison et al. 2003), which is now active in the eastern part of the delta (Akter et al, 2016).

Fourteen sub-regions were delineated based on the river system for discussing the sediment budget (**Figure 6.13**) based on the computed historical files. According to the computed results, about 22% of sediment was deposited in the delta system for floodplain and tidal plain development and river morphology development. All the systems are trapping sediment, except three systems- Ganges, Jamuna, and Upper Meghna rivers system. The sediment in and out of the Ganges system is found to be balanced. But, Upper Meghna and Jamuna rivers are found to produce sediment to the system. In all the estuary systems, like- Shahbazpur channel, Tentulia Channel, Burishwar-Payra, Bishkhali, Baleshwar, Passur-Sibsa, sediment is mostly in suspension mode due to strong back and forth tidal current movement. These well-mixed estuaries are experiencing strong bed shear and vigorous vertical mixing (Wilson and Goodbred, 2015). Rest 78% of the sediment has been used for estuary development and loss in the deep ocean bed. A major part of the sediment load in the system is loaded in the estuary system and pro-delta development. The percentage of the loss to the deep is insignificant.

Figure 6.13 shows the net sediment movement in individual sub-regions of the delta. According to the model results, the usual direction of sediment flow for most of the sub-regions is from north to south throughout the year, except for some systems in the tidal regions during the dry season. About 80% of the total sediment is coming from the Ganges River, whereas the Jamuna River carries about 20%. Nearly 78% of the sediment goes out of the system through the estuary systems, such as Shahbazpur Channel, Tentulia Channel, Burishwar-Payra, Bishkhali, Baleshwar, and Pussur-Sibsa, which is very close to the long-term sediment budget given by Goodbred & Kuehl (2000a). They budgeted that one-third of the sediment carried by these rivers is deposited on the floodplain and tidal plain, one-third is trapped in the sub-aqueous delta, causing vertical accretion and lateral progression of the sub-aqueous delta, and the remaining portion is transported to the deep ocean floor. However, most deposition-prone sub-regions are Padma, Gorai, Arial Khan, Lower Meghna, Shahbazpur Channel, and Pussur-Sibsa rivers. Most of the sediment in the estuary systems, like Pussur-Sibsa, Baleshwar, Bishkhali, and Burishwar-Payra, remain in suspension.



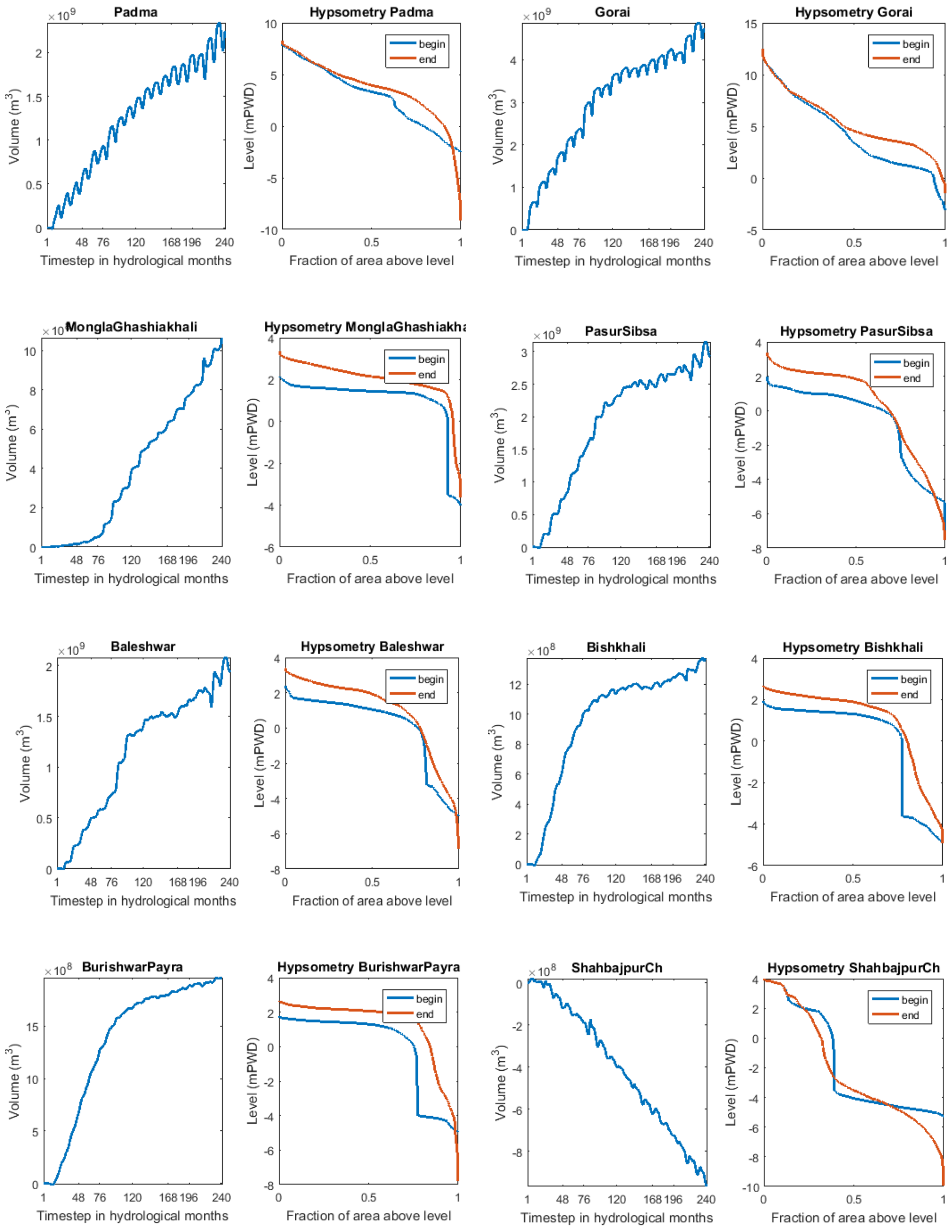
River System	In	Out	Storage
Padma	504	410	94
Gorai	110	105	5
Mongla-Ghashiakhali	2	1	1
Pasur-Sibsa	121	111	10
Baleshwar	65	61	4
Bishkhali	17	10	7
Burishwar-Payra	24	18	6
Shahbazpur Channel	174	133	41
Lower Meghna	233	224	9
Tentulia Channel	195	170	24
Arial Khan	175	92	83
Ganges	566	565	0
Jamuna	132	143	-11
Upper Meghna	3	4	-1

Negative value indicates 'Change in sediment flow direction' or 'Net loss of sediment in the system'

Total_In = 701 Mt/yr
Total_Out = 503 Mt/yr
Total_Storage = 197 Mt/yr

The arrows in the map show the direction of net sediment transport

Figure 6.13: Map showing the sub-region based on the river system.


Padma
Hypsometry Padma
Gorai
Hypsometry Gorai
MonglaGhashiakhali
Hypsometry MonglaGhashiakhi
PasurSibsa
Hypsometry PasurSibsa
Baleshwar
Hypsometry Baleshwar
Bishkhali
Hypsometry Bishkhali
BurishwarPayra
Hypsometry BurishwarPayra
ShahbajpurCh
Hypsometry ShahbajpurCh
Volume (m³)
Level (mPWD)
Timestep in hydrological months
Fraction of area above level
×10⁹
×10⁸
1
48
76
120
168
196
240
0
0.5
1
begin
end

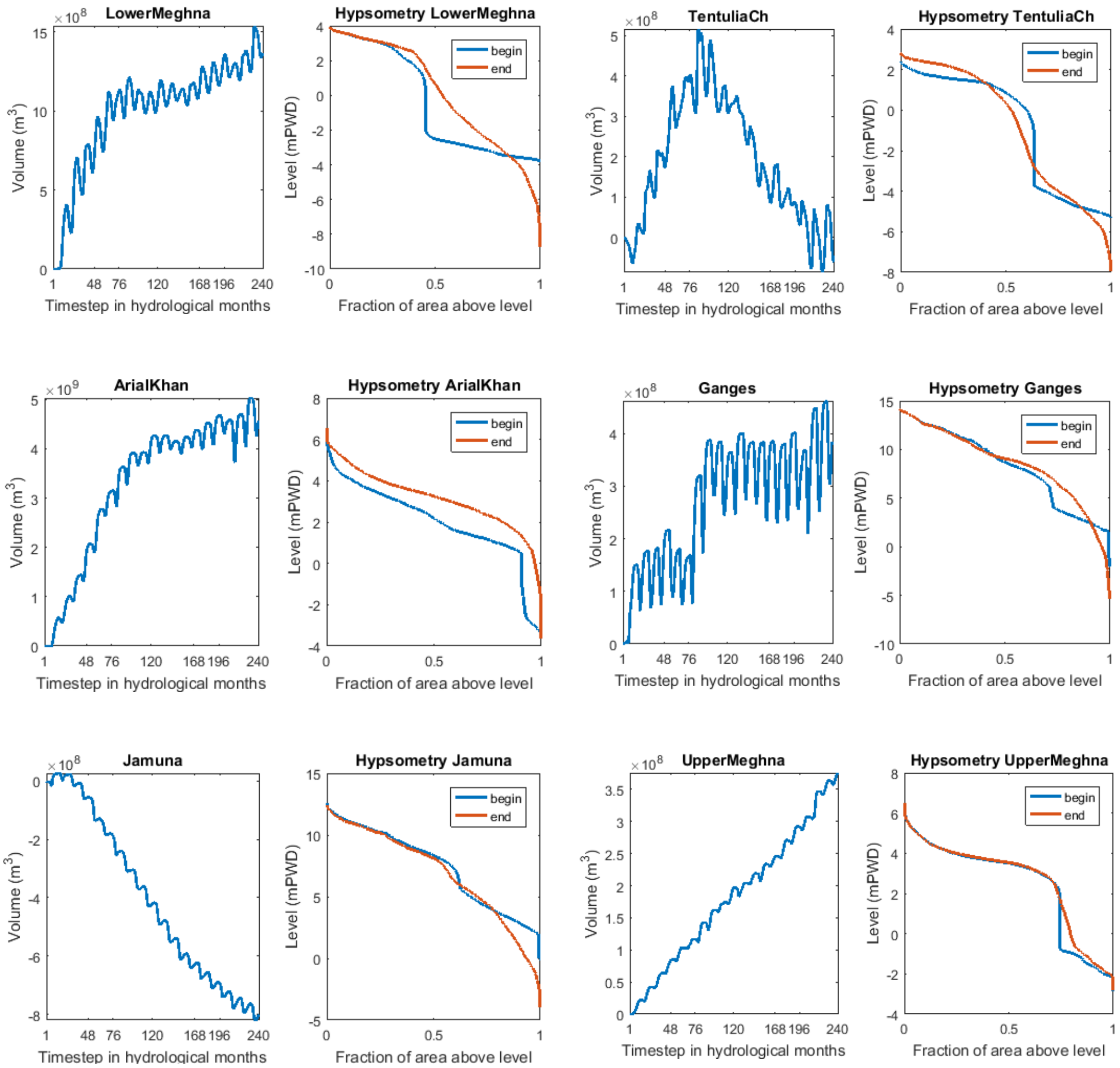
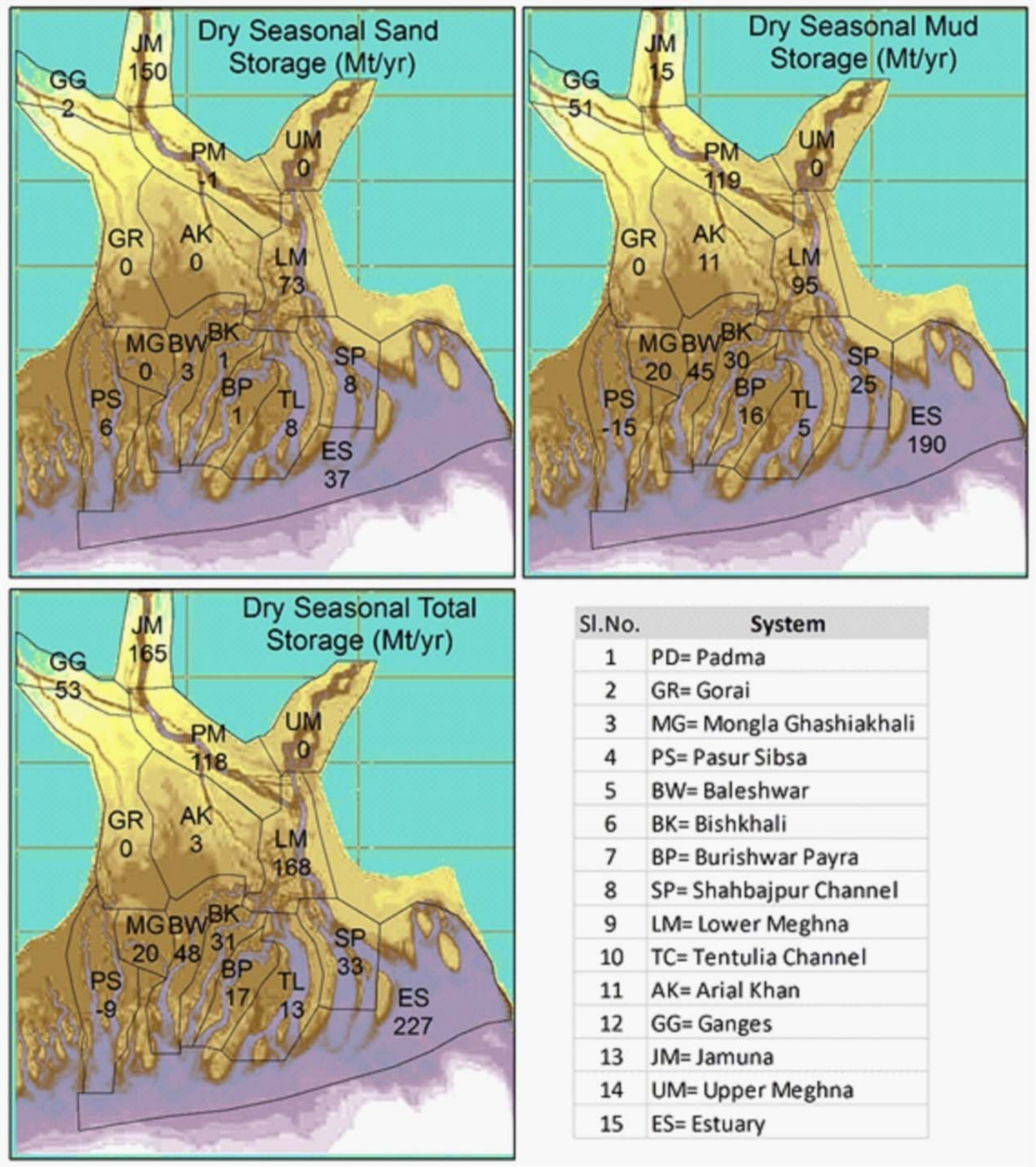


Figure 6.14: Morphological changes over time in the systems

Figure 6.14 (left panel) shows the morphological changes in the systems over time and **Figure 6.14** (right panel) shows hypsometry changes. The figures for 14 sub-regions specify that the Ganges, Jamuna, Padma, Gorai, Upper Meghna, and Lower Meghna sub-regions are experiencing sediment deposition in the low-level areas and little changes in the high-level areas. On the other hand, sub-regions of Arial Khan, Mongla-Ghashiakhali, Pussur-Sibsa, Baleshwar, Bishkhali, and Burishwar-Payra have depositional phases throughout the entire regions.

6.4.3 Seasonal Sediment Budget

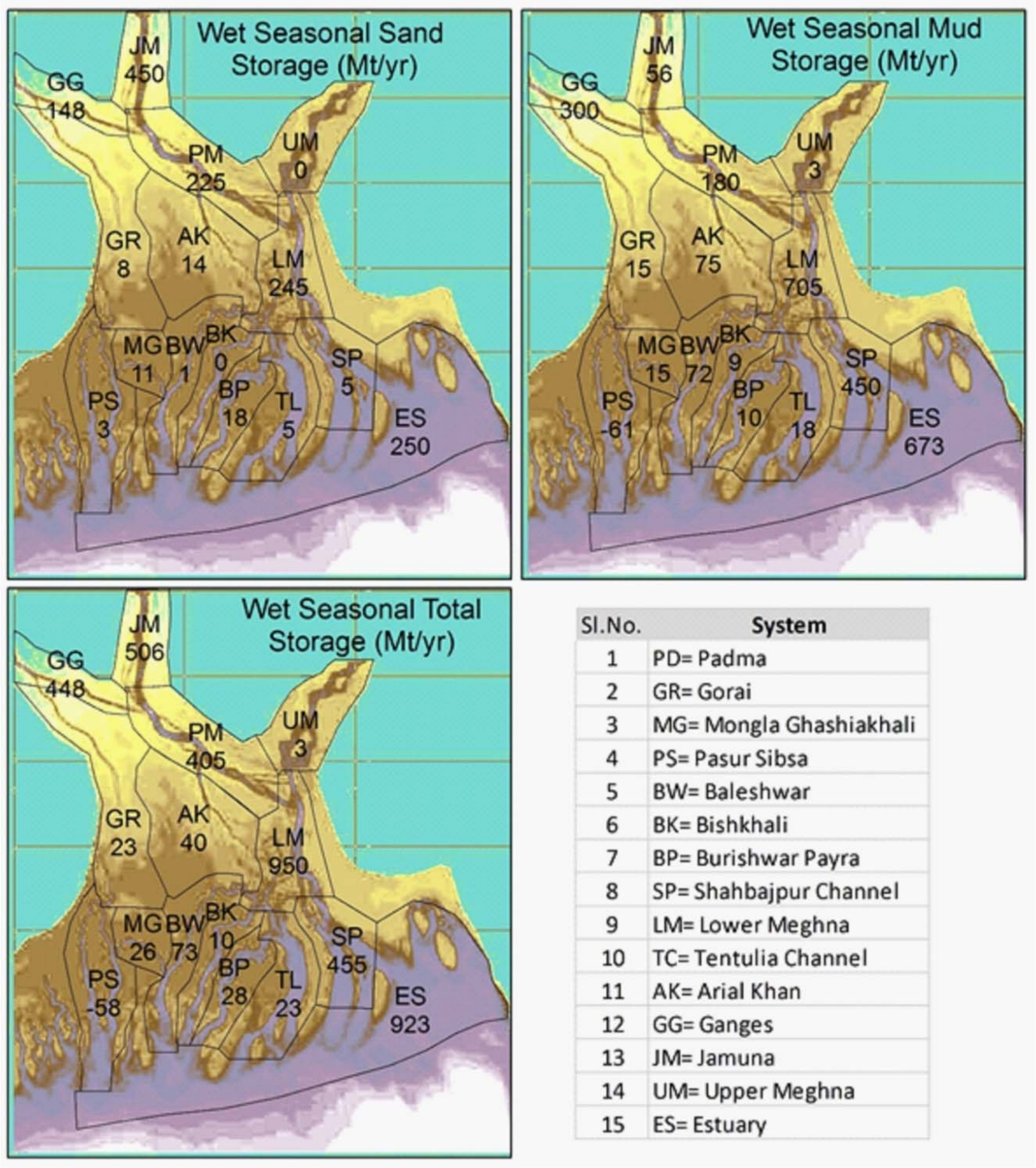
November to May has been considered as a dry period and June to October as a wet period in a hydrological year. With similar consideration of the modelling outputs, an estimation has been done for assessing seasonal and region-based storage in million ton per year. The positive magnitude of storage means an accumulation of sediment and the negative magnitude means loss of sediment from the sub-region. A new region 'Estuary System (ES)' was considered in the estuary area until -7 m depth. **Figures 6.15 and 6.16** show dry and wet season storage in different sub-regions respectively, based on computed historical files.



Sl.No.	System
1	PD= Padma
2	GR= Gorai
3	MG= Mongla Ghashiakhali
4	PS= Pasur Sibsa
5	BW= Baleshwar
6	BK= Bishkhali
7	BP= Burishwar Payra
8	SP= Shahbajpur Channel
9	LM= Lower Meghna
10	TC= Tentulia Channel
11	AK= Arial Khan
12	GG= Ganges
13	JM= Jamuna
14	UM= Upper Meghna
15	ES= Estuary

Figure 6.15: Map showing dry seasonal sediment storage (Mt/year)

Figure 6.15 (upper left panel) indicates that most of the upstream sub-regions have no sand accumulation during the dry period, but net loss. On the other hand, sand accumulation has been found in the coastal regions. But then again, the upper right panel of **Figure 6.15** shows that Gorai, Burishwar, and estuary regions have more mud accumulation. The yearly total (sand and mud) accumulation in the estuary area is 710 million ton/year, as found in **Figure 6.15** (lower left panel).



Sl.No.	System
1	PD= Padma
2	GR= Gorai
3	MG= Mongla Ghashiakhali
4	PS= Pasur Sibsa
5	BW= Baleshwar
6	BK= Bishkhali
7	BP= Burishwar Payra
8	SP= Shahbajpur Channel
9	LM= Lower Meghna
10	TC= Tentulia Channel
11	AK= Arial Khan
12	GG= Ganges
13	JM= Jamuna
14	UM= Upper Meghna
15	ES= Estuary

Figure 6.16: Map showing wet seasonal sediment storage (Mt/year)

Wet seasonal sand storage as shown in **Figure 6.16** (upper left panel) shows that coastal sub-regions have mostly accumulation. On the contrary, wet seasonal mud storage (**Figure 6.16** right panel) mainly occurs in Ganges, Padma, Lower Meghna, Passur, Baleshwar, Bishkhali, Burishwar-Payra, Tentulia, and Shahbajpur regions. Therefore, wet seasonal total accumulation in the ES (**Figure 6.16** lower left panel) is about 440 million ton/year.

However, less than twenty percent of sand is flowing through the system. Net sediment accumulation is found in most of the regions, except the Passur-Sibsa system. The total accumulation in the ES is 1150 million ton per year, out of which more than eighty percent of sediment is in suspension (considering mud component).

6.4.4 Bed Level Changes

The Ganges, Jamuna, and Upper Meghna systems are the boundary for this 2-D model. They are morphologically very dynamic, but we might have limited them by imposing boundary conditions for a better simulation. Among others, the box plot of the systems of Tentulia, Shahbajpur, Bishkhali, and Lower Meghna is found to be larger due to a part of the delta building process in the Meghna Estuary system.

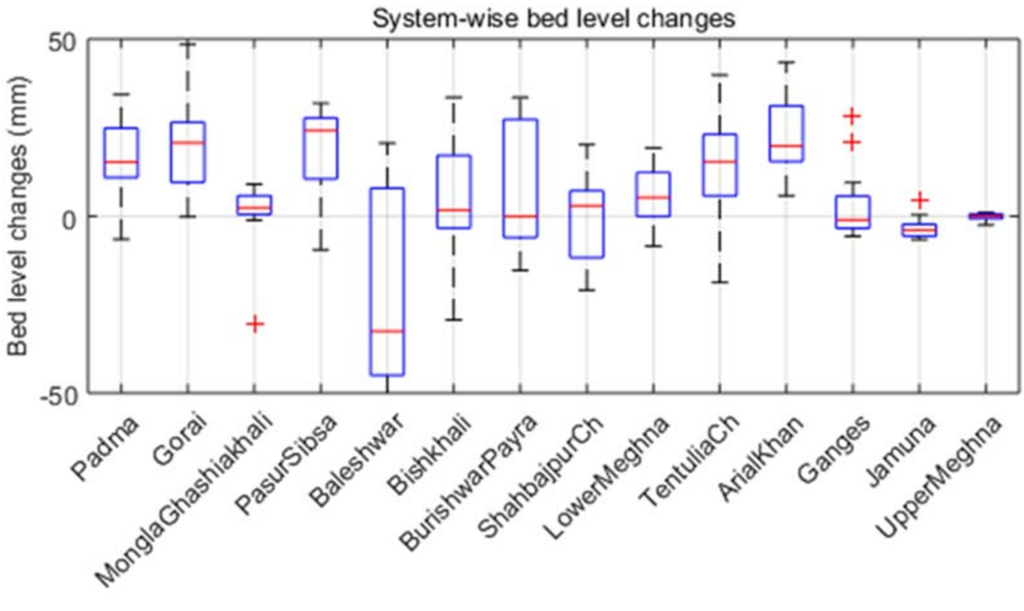


Figure 6.17: Bed-level changes in the rivers system

Comparing the mean values of bed level changes in **Figure 6.17**, it reveals that the Padma, Gorai, Pussur-Sibsa, Bishkhali, Shahbajpur channel, Lower Meghna, Tentulia Channel, and Arial Khan rivers are mainly in the aggrading phase, although they vary spatially and temporally. On the contrary, the Ganges, Jamuna, and Baleshwar rivers are mainly in a degrading phase. However, Jamuna River is also found to be in the aggrading phase in a few years of the simulation period. About 22% of the total sediment coming into the system was deposited in the floodplains and tidal plains, although Rogers et al. (2013) found it as ~10%.

Analysis of sediment load in the systems shows that suspended sediment loads differ about one order more than that of bedload. Bed loads in all systems show transportation through fluvial advection, whereas suspended loads stay in suspension advected by the combined effect of fluvial and tidal flow. The worldwide sediment budget is a challenge due to a lack of data (Vörösmarty et al., 2003). This study may help provide a new argument for future research, although sediment load varies due to seasonal rainfall in the catchments, decadal response to engineering works, and centennial to millennial response due to climate change (sea-level rise and melting of ice sheets).

6.4.5 Sediment Concentration

According to the model results, Shahbajpur and Tentulia channels are the most turbid zones, followed by the Pussur-Sibsa Estuary, due to high suspended sediment concentration that can be translated into turbidity using empirical relations (Achete, et al. 2015). The sediment concentration in the Shahbajpur and Tentulia channels is mainly river-borne during monsoon and tides rework during dry periods (Akter et al., 2016; Sarker et al., 2011). On the other hand, in the Pussur-Sibsa Estuary, the zone is erosion-prone as that is a part of the moribund delta where there is almost no fluvial sediment input. Other than eroding the coastal land, sediment enters into the system from the sea deposited from the active Meghna estuary (Akter et al., 2016).

Coleman (1969) reported that the average suspended sediment concentrations in the Ganges and Jamuna are 1300 mg/l and 1006 mg/l respectively. In our model simulation, we have calculated all the concentrations at the output end of the system, which are the estuaries of the system. We have found that sand is transported only during flood months (timing is proportional to the fluvial discharge). Model results show that Jamuna is the dominant sand source, with maximum concentration ranges from 70 to 150 mg/l, followed by the Padma which has a sand concentration ranging from 25 to 60 mg/l. On the other hand, the Ganges (40-240 mg/l), Gorai (70-215 mg/l), and Padma (80-170 mg/l) have the highest mud concentrations. Both the sand and mud concentrations drop significantly at Chandpur. But around Urir Char, the mud concentration could be as high as 300 mg/l, where maximum sand concentration is found to be as low as 10 mg/l.

Varying seasonally suspended sediment concentration in the Bishkhali, Burishwar, Tentulia, Shahbajpur estuaries ranges from 23 to 91 mg/l. However, Wilson and Goodbred (2015) and Sokolewicz and Louters (2008) mentioned that suspended-sediment concentration in the GBM river-mouth estuary range from 5 to 90 mg/L with a seasonal variation over spring-neap tidal cycles.

6.5 Conclusions

This is the first attempt to develop a detailed, process-based model for the GBM delta. Along with observed data, numerical modelling can help to understand morphodynamic development and changes on a long-term scale and is potentially a powerful tool to investigate the formation and controlling mechanisms of morphodynamics (Stive and Wang, 2003; Roelvink and Reniers, 2011). A numerical Delft3D model was developed to examine whether it can simulate a large delta system and produce a long-term sediment budget for the GBM delta. Domain bathymetry was prepared from different sources with some modifications. Model parameters were selected after many parallel simulations with the same sets of data for producing a better result. Later on, model performance was validated both in hydrology and morphological patterns. Model results were compared with observed water levels at Tazumuddin, Nilkamal, Chandpur, and Mawa. All these locations cover both tidal and fluvial regions. The tidal dampening process was visible in the model results based on the distance from the river mouth. The morphological pattern developed by the model was found to be very similar to the planform of the rivers in 2005. Although, there are still many ways to improve the model.

This research suggests that the range of average sediment transport of the Ganges and Jamuna systems are 216-1038 million ton/year and 80-228 million ton/year respectively, whereas the transport in the Upper Meghna River is negligible. The trends of the sediment loads found in different research are found to be decreasing as time progress to recent years. The reason is attributed to less sediment production in the catchment by a natural event like landslides and, better sediment management, and sediment trapping by dam/barrage construction in the upper regime. About 22% of sediment was deposited in the delta system for floodplain and tidal plain development and river morphology development, whereas the remaining 78% of the sediment was used for estuary development and lost in the deep ocean bed.

Yearly, less than twenty percent of sand is flowing through the system; its range varies region-wise. Net sediment accumulation is found in all the regions. The total accumulation in the estuary system is 1150 million ton per year, out of which more than eighty percent of sediment is in suspension. A major part of the sediment load in the system is lost in the estuary system and pro-delta development. The percentage of the loss to the deep is insignificant.

Nonetheless, the most deposition-prone sub-regions are the Padma, Gorai, Pussur-Sibsa, Bishkhali, Shahbajpur channel, Lower Meghna, Tentulia Channel, and Arial Khan rivers. Most of the sediment in the estuary systems, like Pussur-Sibsa, Baleshwar, Bishkhali, and Burishwar-Payra, remain in suspension. Analysis of bed level changes over time, reveals that Padma, Gorai, Pussur-Sibsa, Bishkhali, Shahbajpur channel, Lower Meghna, Tentulia Channel, and Arial Khan rivers are mainly in the aggrading phase, although they vary spatially and temporally.

There is still much scope to improve the model. Measured sediment data in the study area is very limited and does not cover the whole system. Although modelling works cannot reproduce the complete natural phenomena, for macro-scale understanding, planning, and management it is proven to be the best tool that is suitable in terms of cost and time. As the model can accommodate various relevant prevailing processes that can alter the delta system, it would help make future management decisions. This particular GBM delta model offers many opportunities to test with the sediment data, where it deals with a poorly surveyed area. Further work with a finer-resolution model may support a higher temporal and spatial variation of bottom friction, sedimentation, and erosion.

Chapter 7

Conclusions and recommendations

This last chapter draws conclusions based on the research objectives and questions formulated in Chapter 1. A summary has been made to target answering the research questions. Finally, a few recommendations are proposed.

7.1 Concluding Remarks

7.1.1 Introduction

The general aim of this thesis was to assess the decade to century-scale geo-morphological development of the Ganges-Brahmaputra-Meghna (GBM) Delta, the so-called Bengal delta, that will lead to improved understanding of the existing processes in the system. Long-term process-response understanding of this delta system would help to increase the predictability of the delta building processes.

To understand the century-scale morphological process of the delta system, historical maps of Rennel's (1776), Tassin's (1840), and Topo-map of 1943 were used. On the other hand, time-series satellite images since 1973 were used from CGEIS' archive for constructing decade-scale morphological processes. The rate of net accretion was enormous on both a centennial and decade scale. The 1950 Assam earthquake, new-tectonics, and delta-building processes were all-important external influences.

It was difficult to work with a data-scared delta system. The GBM delta is a good example of a huge system lacking data. Not even a complete momentary bathymetric data set was recorded. Datasets of continuous river flow or water levels were present for a very limited number of stations. A different approach was adopted for carrying out this research. Numerical models help to create a unique virtual laboratory system with simple or multiple complex processes.

At first, a process-based 1-D morphodynamic model, with Delft3D, was used for understanding whether the Meghna estuary is aggrading, degrading, or tends to attain morphodynamic equilibrium in the coming decades since many people depend on its course for daily life. Series of sensitivity analyses were carried out for assessing the effects of varying mean sea level (MSL), depth at the river mouth, river-bed slopes, bed roughness, and the shape of the river width. Though highly simplified and based on rough assumptions considering the initial bathymetry due to a lack of data, the 1-D model reproduces water levels in promising agreement with scarce, measured water level data. The insights gained with this 1-D approach will be useful for further 2-D simulations.

In the second step, a 2D process-based morphological model, Delft3D, was used to reproduce the bathymetric evolution over time and the associated sediment budget. The morphological pattern developed by the model was found to be very similar to the planform of the rivers in 2005. Still, there are many ways to improve the model. Although modelling works cannot reproduce the complete natural phenomena, for macro-scale understanding, planning, and management, it has proven to be a valuable tool.

7.1.2 Answers to the Research Questions

In the context of the research scopes with a process-response modelling tool, the answers to the research questions as listed in Chapter 1 are elaborated in the following:

Research Questions 1: What are the prevailing processes, on a decadal to century time-scale, in the Ganges-Brahmaputra-Meghna system in forming the tide-dominated delta?

The answer to this question is illustrated in Chapter 3.

A comprehensive literature review is an overview of past research on the subject which helps to understand the prevailing process in a system. The whole analysis was done based on time scales of centuries to decades. For the construction of the centennial-scale processes, historical maps of 1776, 1840, and 1943 have been used; whereas that of decadal-scale, time-series satellite images since 1973 have been used. There are significant differences in opinions and varying findings in the literature when it comes to the prevailing processes in the GBM system and delta's response to various natural and human interventions. The delta and estuary system's behaviour has been examined at different time scales, and the estuary's history has been reconstructed over the previous 250 years to identify major events and drivers at various scales.

Human interventions or disturbances on a big scale influence the entire estuary. Tidal characteristics, in addition to changes in fluvial input, have a major influence on the morphology and migration of islands. In the last 242 years, from 1973 to 2018, Bhola moved 50 kilometers to the south, Hatiya 30 kilometers, and Sandwip a few kilometers. In connection to the identified events, erosion and accretion processes were found to be extremely erratic on both a centennial and decadal-scale.

Characteristics and formation processes of the Bengal delta and estuaries include river shifting and avulsion, delta shifting, tidal plain sedimentation, delta progradation, erosion-accretion processes in the GBM Rivers, coastal areas, Meghna estuary, and its associated islands, and salinity intrusion. Among other natural processes, sediment dispersal process, land formation process, migration and elongation process of islands, stability of the islands, subsidence, impacts of SLR, and so on are mention-worthy. Human interventions in the first half of the last century, found as recorded in literature, and major connectivity for reducing the navigation length, as- Halifax cut in 1910, 23-km Madaripur Beel Route during 1910-12, 118 km Gabkhan Channel, and Mongla-Ghashiakhali Canal in 1974 are worthy to be mentioned. All these connections modified the hydrological regime significantly. Furthermore, unplanned railways and highways construction over the floodplain has restricted the free flow of floods over the terrain.

Several flood embankments and polders were built in the floodplain and tidal plains throughout the second part of the 20th century with the purpose of better water management and increased food production. The Farakka Barrage (since the 1960s) in India, which diverts water from the Ganges to support the Kolkata port, has significant consequences for southwest Bangladesh hydrology. Many rivers and tidal channels perished in a matter of years to decades. All of these human activities have resulted in drainage congestion and sediment erosion inside the polder, as well as excessive sedimentation in river channels, producing tidal amplification and decreased navigability.

Regarding climate change, all the relevant studies agree that temperature will increase. An increase in temperature of 0.75^0C, 1.55^0C, and 2.4^0C would cause a median precipitation increase of 1%, 4%, and 6% in 2030, 2050, and 2080 respectively. The study projected that increase of the average discharge in August and September, would be about 10%, 12%, and 7% in the Brahmaputra, Ganges, and Meghna, respectively. However, climate change associated with increased rainfall would undoubtedly increase the flood discharge in the river system causing corresponding inundation in the floodplain and tidal plain. In addition, SLR would increase the spatial and temporal extent of tidal flooding. So, both the increased rainfall and SLR would cause an increase in inundated area and depth. More than 50% of the Bangladesh delta is less than 5 m above mean sea level, based on the available digital elevation model.

Research Question 2: What are the climate change-related global and regional projections?

The answer to this question is stated in detail in Chapter 4.

The major cause of all the variables is an increase in temperature (global warming). As stated in IPCC 2013, the Global mean sea level exceeded 5 m above present during the pre-industrial period when the global temperature was 2^0C higher. Most studies have identified Bangladesh as one of the world's most vulnerable countries to climate change. Bangladesh is experiencing increased cyclones, tidal surges, erosion, flooding, salinity intrusion, and other effects as a result of climate change.

The Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) projected global average surface warming, global SLR, and South-Asian precipitation under different scenarios. AR4 (IPCC, 2007) estimated that the maximum amount of global average SLR over the twenty-first century would be in the range of 0.26 m to 0.59 m, whilst world temperature would rise by 2.4-6.4ºC. The anticipated increase in monsoon seasonal rainfall for South-Asia under the same scenario is 26%. According to the IPCC's Fifth Assessment Report (AR5), the global mean temperature will rise by 4.49 degrees Celsius under the A1FI scenario. SLR projections are also greater in AR5 than in AR4, owing to the inclusion of land-ice impact in their enhanced modelling effort (IPCC, 2013). The global mean sea level is predicted to increase between 0.53 and 0.98 meters under the RCP8.5 scenario. Similar projections for July precipitation in South Asia, which is the predominant yearly rainfall. Bangladesh's rainfall would significantly increase (IPCC, 2013).

Although trend analysis of short-term temperature and rainfall data is unreliable owing to time scale variations. Although there is no significant changes in temperature and rainfall data in Bangladesh from the 1960s to 1993, even still, according to the IPCC's business-as-usual scenario from 1990, rainfall would increase as the temperature rose.

According to an empirical model, the greatest change in precipitation in the Ganges Basin and the Brahmaputra Basin with a temperature increase of 2^0C would be 13 percent and 10.2 percent, respectively. Increases in precipitation in the Ganges and Brahmaputra basins would result in 21.1 percent and 6.4 percent increases in mean annual flow, respectively. Another study discovered that a 13 percent increase in precipitation over the Ganges basin would result in a 22 percent increase in peak flow at the Ganges River's Hardinge Bridge. Nonetheless, any rise in temperature or rainfall in the watershed will increase the downstream discharge in all situations.

A recent study found that predicted the consequences of climate change on Bangladesh for three different periods: 2030, 2050, and 2080. For those three time periods, they predicted temperature rises of 0.75^0C, 1.55^0C, and 2.4^0C, respectively, with median precipitation increases of 1%, 4%, and 6%. As a result, by 2050, the monsoon discharge would be higher, but the monthly growth rates would be different, based on five generator condition monitors and two special reports on emissions scenarios model experiments. The prices, however, would differ depending on the river. In two monsoon months, August and September, the average discharge would be increased. In the Brahmaputra, Ganges, and Meghna rivers, the average discharge increase in two monsoon months, August and September, would be around 10%, 12%, and 7%, respectively.

Research Question 3: How can a process-based 1D model describe the Ganges-Brahmaputra-Meghna delta morphodynamic evolution?

The answer to this question is illustrated in Chapter 5.

Developing a 1-D process-based morphodynamic model to explore the first-order dynamics of GBM bathymetry helps us to generate a set of data for a data scars study area. A series of sensitivity analyses were carried out for assessing the effects of varying mean sea level (MSL), depth at the river mouth, river-bed slopes, bed roughness, and the shape of the river width. Though highly simplified and based on rough assumptions considering the initial bathymetry due to a lack of data, the 1-D model reproduces water levels in promising agreement with scarce, measured water level data. Sensitivity simulations suggest that seasonal variation in the MSL has a strong impact on the hydrodynamic behaviour of the GBM system. The insights gained with this 1-D approach will be useful for further 2-D simulations. The morphodynamic 1-D model shows that an equilibrium configuration occurs within a millennium scale, with bed aggradation in the downstream delta system. This may trigger a significant change in hydro-morphology, including river system avulsion.

Overall, both the river and marine reaches demonstrate deposition in the bed profiles. The river bed profile was first discovered to be degraded, most likely as a result of morphological adjustment owing to boundary forcing. Deposition occurred shortly after Nilkamal, at the mouth of the estuary, when the river geometry had begun to widen. The sedimentation front after the river mouth was determined to be net propagating seaward more than 50 km in 50 years, according to the computed results. Because there was neither inflow nor outflow at the sea border, no silt was leaving the domain.

In reality, the estuary corresponds to a region with bars/islands, which can't be replicated by a 1D model. However, the computed findings show consecutive riverbed upgradation, which might suggest shallow water depth in that area. The estuary area may create a sequence of bars/islands to maintain the appropriate water slope between specified locations and the river mouth.

In the case of century-scale bed profile changes, the computed results show continual bed level aggradation. Until the end of the simulation, a propagating sedimentation front (delta front) has also been seen in this long-term simulation. In the model, bed-level aggradation shows a shallower river depth, which in actuality may result in a widening of the river width, which cannot be replicated at this 1D model because the width was constant in the outer reaches. It might also cause avulsion in the delta system. The propagation of the tides throughout the system would be affected by river bed aggradation and water level rise in the estuary.

In reality, as the profile expands, there will never be balance. However, the model was run for 400 years in this work, and no equilibrium bed profile was observed during that time under the same boundary force. After 200 years, morphological growth slowed dramatically. As a result, in this long-term simulation, century-scale bed profile changes, we cannot assume any equilibrium bed profile during the simulated time.

Numerous studies have highlighted SLR and subsidence in the GBM delta. For this analysis, however, a 0.006 m/year SLR and 0.002 m/year subsidence assumption were used for 100 years of climate change scenarios. Starting with a linear bed, the bed profile evolves with and without climate change scenarios. In the climate change scenario, due to SLR and subsidence, the aggradation rate would be somewhat greater. Bed development would be higher in the absence of climate change, particularly close upstream of the river mouth. The river mouth's apex would grow more vertically and horizontally. The delta front would propagate a few kilometers less in the SLR and subsidence scenario, on the other hand. The bed would aggrade by a few millimeters in the higher reaches, but there would be less deposition along the sedimentation front. But, the delta front would transgress a few meters towards the land.

This 1D computation presented a straightforward way of describing a large complicated system with the least amount of data and information. This approach is particularly useful when data are scarce. The system parameters may be assumed via a simple 1D modelling exercise. This work, on the other hand, shows that 1D modelling can provide hydrodynamic similarities with the observed datasets. It also suggests that even after 400 years, the overall system may not attain equilibrium.

Research Question 4: How can a process-based, 2-D model describe the Ganges-Brahmaputra-Meghna delta morphodynamic evolution?

The answer to this question is illustrated in Chapter 6. Affirmatively, this robust 2D model is applicable to assess the morphodynamic evolution.

Using a unique technique for creating depth data for the model, the usage of a full modelling system to assess morphodynamic development, sediment budget, and pathways was presented. We used morphological patterns and trends from satellite pictures and observations to analyze the decadal-scale morphological model output. Because it was dealing with a little-studied location, this delta model was expected to give numerous opportunities for comparison with sediment data.

Erosion and sedimentation during 100 morphological years were generated from the 2-D modelling. The modeled domain's evolution patterns were extremely varied initially, but the process slowed later and it did not reach equilibrium until the conclusion of the simulation period. During every monsoon, there was a pulse of evolution. The land development/ adjustment at and around the river boundary demonstrates that the Padma-Lower Meghna River System is undergoing land development. It's also active in the floodplains of the Arial Khan River. During the previous few decades, land development in the Urir Char region (the northeast tip of the bay) has been very consistent with reality.

In the GBM rivers, the model was able to produce char lands. It was unable to replicate tiny islands in other sections of the fluvial regions because of the coarse grid. The morphology of rivers and estuaries is influenced by these types of characteristics. They're in charge of everything from channel migration to river avulsion to channel abandonment. They are in charge of guiding river flow and sedimentation in the riverbed, as well as riverbank erosion. A fairly similar pattern was replicated by the model. The pattern of planform evolution is predicted to be recreated more efficiently using a finer grid and long-term simulation. The planform patterns of the Padma and Lower Meghna, as well as the island growth in the river and estuary system, are found to be extremely close to the observed patterns in the satellite picture of 2005 in this model result.

The model findings replicate the evolution pattern of the GBM estuaries, with increasing seaward propagation of shoals, tidal flats bordering the western side, sequential filling in the north-east side of the BoB (around Urir Char region), and subsequent seaward migration of the river mouth. Downstream river-borne sediment flushing causes gradual channel and shoal modifications. The overall large-scale channel-shoal patterns have been consistent in recent decades, owing to a more solid coastline for establishing coastal embankment. Nonetheless, the embankment might break as a result of tremendous pressures in the channel. Continuous small-scale erosion and deposition are happening outside the embankment and in unprotected shoals, particularly in the sea-exposed marine zone.

Research Question 5: Would the application of the 2D model be robust enough to assess current date morphodynamic evolution and sediment budget?

The answer to this research question is provided in Chapters 6. The 2D model is robust enough to assess current date morphodynamic evolution and sediment budget.

A long-term sediment budget was calculated for fourteen regions. Approximately 22% of sediment is deposited in the delta system for floodplain and tidal plain development, as well as river morphology development, according to computed findings. Except for three systems: the Ganges, Jamuna, and Upper Meghna rivers, all of the systems retain silt. It has been discovered that the silt entering and leaving the Ganges system is balanced. However, the Upper Meghna and Jamuna rivers have been shown to contribute silt to the system. Sediment is largely suspended in all estuarine systems, including Shahbazpur Channel, Tentulia Channel, Burishwar-Payra, Bishkhali, Baleshwar, and Passur-Sibsa, due to significant back and forth tidal current action. Strong bed shear and vigorous vertical mixing are occurring in these well-mixed estuaries. The remaining 78% of the material has been used to build estuaries and has been lost in the deep ocean bed. The estuary system and pro-delta growth are responsible for a large portion of the sediment load in the system. The amount of sediment lost to the deep sea is little.

The delta's net sediment movements in different sub-regions are demonstrated by the model. Except for some systems in tidal zones during the dry season, the normal direction of sediment flow for most of the sub-regions is from north to south throughout the year, according to the model results. The Ganges River accounts for around 80% of total silt, while the Jamuna River accounts for approximately 20%. Nearly 78% of the sediment leaves the system via estuary systems including the Shahbazpur Channel, Tentulia Channel, Burishwar-Payra, Bishkhali, Baleshwar, and Pussur-Sibsa, which is extremely near to a study's long-term sediment budget. According to research, one-third of the sediment carried by these rivers is deposited on the floodplain and tidal plain, another third is trapped in the sub-aqueous delta, producing vertical accretion and lateral advancement, and the other third is transported to the deep ocean bottom.

This current research illustrated that the Padma, Gorai, Arial Khan, Lower Meghna, Shahbazpur Channel, and Pussur-Sibsa rivers, on the other hand, are the most deposition-prone sub-regions. The majority of the sediment in estuary systems such as Pussur-Sibsa, Baleshwar, Bishkhali, and Burishwar-Payra is suspended.

7.2 Recommendations

Based on this study, few recommendations are made below to advance system understanding of the GBM Delta in view of adaptation to Climate Change driven developments:

- Although several studies have addressed the Holocene development of the Bengal Delta, there are no significant studies, apart from a few micro-scale studies, that address 'the decade to century-scale development' of the whole delta (Partially filled up by this research). The unavailability and unreliability of sediment data restrict scientists to work on this issue. The strengthening of the sediment monitoring system in Bangladesh needs to be addressed. For real sediment data, more stations should be added to the network with higher measurement frequency. Types of tools and instruments should be selected depending on the hydro-morphological condition of the river systems, like different methodologies for big/small, fluvial/tidal, saline/non-saline, and connected/ disconnected rivers.
- Water and sediment flow measurements in tidal rivers remain to be a challenge. Tidal characteristics of the coastal region need to be classified and data measurement methodology would be suggested specifically for the coastal region.
- Data archiving is another important task to do in the future along with a management system for remote access to the public. Proper data management system and their open and easy access would accelerate the research and planning process in the future.
- Knowledge of the vertical adjustment processes of the tidal plain with the rising of RSLR/ tide level is hardly available. This is an important issue to develop strategies for long-term planning to adapt to climate change-induced sea-level rise. The impact of polderization is also needed to be well-addressed, although some modelling exercises have already been done in this regard. Those computed data should be easily accessible for further research
- Although some indicative research on the morphological time-scale of the rivers, estuaries and tidal plains to adjust with the SLR and increased flood discharge have

been done, some more research needs to be done depending on the availability of sediment in the context of climate change and human interventions for long-term planning of these time-scales.

- Deltaic subsidence is relevant for long-term planning, although recent studies indicate very high uncertainty ranges from 1 mm to 25 mm per year. This study suggests a subsidence rate of 2 mm/year for most of the region of Bangladesh and 6 mm/year along the coast. But, further research on subsidence may provide a more realistic rate of subsidence to rationally plan and design purposes for addressing climate change-induced SLR. As huge cost is involved with every single unit design height of the coastal structural defense, further research is needed for identifying the subsidence rate.
- The impact of the coastal polders has been explored. But, how it has altered the natural land sedimentation process in our system is unexplored till now. The rate of floodplain and coastal plain sedimentation with the changes of SLR or tidal range and also the availability of sediment has not been studied yet. Information on these matters may help formulate the adaptation strategy against climate change and subsidence.
- The main rivers of Bangladesh transport about one billion tons of sediment every year, out of which one-fourth is fine sand. The rest of the sediment consists of silt and clay. There are also indications that the sediment supply has been reducing. The role of fine and coastal sediment in the land accretion process would be different. Knowledge on the role of these fine (silt & clay) and coarse (fine sand) on the lateral and vertical accretion process requires further elaborations for this delta plain.
- Tidal asymmetry plays a key role for sedimentation where no or less upstream flow is coming. We have some knowledge of the effect of the tidal asymmetry in the Mongla-Ghashiakhali (MG) channel. If we know the characteristics of the tidal asymmetry and we add it to the geometry of the channel, we may use any 1-D model to find the responses. We may take the real example of the MG canal. We may develop the geometry of the channel through dredging which will help to reduce the tidal asymmetry. Thus we can re-design a channel for reducing tidal asymmetry which in turn will reduce sedimentation in the river bed. This idea can be applied in other regions also. Hence, Study on tidal asymmetry and sediment concentration for understanding the sedimentation process in the coastal zone.

- Information on tidal asymmetry in the fluvio-marine zone, like-the Meghna Estuary, is also important. In this type of zone, where sediment is available, tidal asymmetry causes the sediment pumping process. We need to know the behaviour of the tide for managing the sediment pumping process in the future targeting new land reclamation in the Meghna Estuary region.
- Finally, the process response model developed under this study, may be used for further development work considering other physical processes to predict the response of the delta in the changed condition for long-term planning. Prevailing processes that are already identified could be incorporated in that process response model for trying out future unequivocal scenarios. The modelling approach applied in this study may be capable to quantify the responses to human-induced and natural events environmental changes in a complex GBM system. More accurate data input to this developed model would offer to minimize the uncertainty associated with over- or under-parameterization.

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Exposure

Publications

1. **Akter, J**.; Nur, F.; and Sarker M.H. (2022). Study of the off-take dynamics for restoring the Old Brahmaputra River. 6th International Conference on Civil Engineering for Sustainable Development (ICCESD 2022), held in Bangladesh, March 2022.
2. **Akter, J.;** Roelvink, D.J.A; and van der Wegen. (2021) Process-based modelling deriving a long-term sediment budget for the Ganges-Brahmaputra-Meghna Delta, Bangladesh. Journal of Estuarine Coastal and Shelf Science, Volume 260, 5 October 2021, 107509. ttps://doi.org/10.1016/j.ecss.2021.107509.
3. Sarker M.H., **Akter J.,** Huque I., Oberhagemann K., Akand M.K. (2021) Formation and Dynamics of Coastal Chars in Bangladesh. In: Zaman M., Alam M. (eds) Living on the Edge. Springer Geography. Springer, Cham. https://doi.org/10.1007/978-3-030-73592-0_9. pp 141-166.
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13. Sarker, M.H. and **Akter, J.** 2011. Evolution of rivers in subsiding Sylhet basin: northeast of Bangladesh, Conference on „ Advances in River Science 2011, 18-21 April 2011, Swansea, United Kingdom.
14. **Akter, J.,** Islam, S. N. and Gnauck, A. 2010. Water resources management in the coastal region of Bangladesh. In: Modellierung und Simulation von Ökosystemen, Shaker Verlag, Aachen , Germany, pp 165 – 185.

Oral and Poster Presentation

1. Assessing the rate of subsidence in the Bengal delta. Deltas in times of climate change II, 24-26 September 2014, Rotterdam, The Netherlands.
2. Decade to century-scale geo-morphological development of Bangladesh. Ph.D. Symposium, Delft, The Netherlands (2014).

- Prevailing processes in a tide-dominated delta: Bangladesh perspective. 36th IAHR World Congress, 27 June-3 July 2015, The Hague, The Netherlands

Training Program

1. Attended an online training and knowledge sharing program (KSP) on rivers and offtakes training, and modelling using Delft3D4 software as a part of the Joint Collaboration Program between Bangladesh and the Netherlands. The KSP was held on Nov 2nd ~25th 2020 with a total duration of 21 hours. She was one of the organizer members and trainers.
2. Attended the IHAR congress 2015 held in The Hague, The Netherlands, as a volunteer and co-chairing of sessions during 27 June – to 5 July 2015 as a part of Young Water Professional.
3. Attended two weeks of NCK Summer Course on Estuarine and Coastal Processes in relation to Coastal Zone Management during June 15-25 June 2015 at Texel, the Netherlands.
4. Attended five-day-long training on “Morphological Modelling Using Delft3D” conducted under Ph.D. program during 15 Sep-19Sep 2014 at UNESCO-IHE, The Netherlands.

About the author

Jakia Akter, with the nickname Nupur, was born on 29 December 1978 in Madaripur, Bangladesh. She is the first child of her parents with three sisters and one brother. He grew up in Dhaka. She attained her Bachelor of Science in Water Resources Engineering (WRE) degree from Bangladesh University of Engineering and Technology (BUET) in 2003 respectively. She admitted herself for MSc (WRE) in the same university in 2005 as a part-time student and avail the MSc degree in 2010. She joined CEGIS (Center for Environmental and Geographic Information Services) in September 2005, where she was engaged in different projects under the water resources division and climate change division. Since 2010, she has been developing her career in River, Coast, and Delta Morphology division.

During her career in CEGIS, she has successfully been carrying out a series of national and international projects as the Project Leader. In addition to that, she has been working as a Hydrologist, River Engineer, Morphologist, and Hydrodynamic and Morphological Modeller in CEGIS. Following are the main projects in that she was actively involved:

- Focal Person of a Working Package (Go with the flow: Old Brahmaputra River) of "Joint Collaboration Program (JCP) between Bangladesh and the Netherlands" for The Netherlands Government during the 2019-till date.
- Focal Person of an Implementation Program on New Land Development in the extended Coastal Zone of Bangladesh under Support for implementation Program of Bangladesh Delta Plan 2100 (SIBDP) during the 2019-till date.
- Project Leader of the "Feasibility Study of river management by enhancing the navigability, minimizing drainage congestion, wetland ecosystem, irrigation and landing facilities in the Khulna Division for supporting M.G channels" for BIWTA during 2019-2020.
- Project Leader of the "Monitoring the performance of the dredging in connection with hydrological & morphological impacts and assessment of the effectiveness of dredging at the outer bar area in the Passur Channel of Mongla Port" for Mongla Port Authority during 2018-2020.
- Project Leader of the "Hydro-morphological Study of Paturia-Daulatdia Ferry Ghats and Layout Plan & Design of Ferry Ghats & Terminal Building" for BIWTA during 2018-2019.

- Morphologist of the “Institutional Strengthening and Project Management Consulting Services for FRERMIP Project-1” for Euroconsult Mott MacDonald during 2015-2018.
- Morphologist of the “Delta Plan 2100” for Bangladesh Government during 2014-2018.
- Project leader of the “Morphological analysis of various rivers in support of RTW hydro-technical investigations on major rivers” for Regional Cooperation and Integration Project-Rail Component during 2013-2014.
- Project Leader of the “Assessing health, livelihoods, ecosystem services and poverty alleviation in populous deltas” with UK Department for International Development (DFID), the natural Research Council (NERC), and the Economic and Social Research Council (ESRC) during 2012-2016.
- Project Leader/ Morphologist/ Hydrologist of the “Hydrological Survey on BSCIC Industrial park, Sirajganj” with Bangladesh Small and Cottage Industries Corporation (BSCIC) in 2013.
- Morphologist of the “Data Collection Survey on Water resources Management in Haor Area of Bangladesh” with NIPPON KOEI CO. Ltd. (the JICA Study Team) in 2013.
- Project Leader/ Hydrologist of the “A Large River Flood and Bank Erosion Risk Management Program” with Northwest Hydraulic Consultants Ltd., Dhaka, Bangladesh in 2012.
- Morphologist of the “Environmental and morphological impact assessment on the rivers of Sylhet region due to mechanical extraction of stone, gravel, and sand” with Department of Environment during 2012-2013.
- Morphologist of the “Consultancy Services for Geo-morphological & Planform Studies with Environmental and Social Impact Assessment on Study of Capital Dredging and Sustainable River Management in Bangladesh” with Bangladesh Water Development Board during 2011-2013.
- Morphologist of the “Preparation of the Haor Master Plan” with Bangladesh Haor and Wetland Development Board during 2010-2011.
- Project Leader and Water Resources Engineer of the “Bank erosion and navigability problem in the River Arial Khan from Madaripur launch ghat to Kalikapur-Habiganj-Rajarhat-Srinadi via Tekerhat river route” with Bangladesh Inland Water Transport Authority in 2011.
- Mid-level Morphologist of the “Morphological analysis of Padma River in connection with the design of the Bridge” with Consultant of detailed Design of Padma Multipurpose Bridge Project in 2009.

- Project Leader and Water Resources Engineer of the “Development of a book and a database of ‘Rivers of Bangladesh” with Bangladesh Water Development Board during 2010-2011.
- Project Leader of the “Preparation of Position Papers showing sustainable water sharing options of common/border rivers” for Joint Rivers Commission, Bangladesh during 2008-2011.
- Junior Mathematical Modeler of the “Consultancy services in connection with Drainage Improvement of Dhaka-Narayanganj-Demra (DND) Project” for Bangladesh Water Development Board in 2007-2008.
- Junior Mathematical Modeler of the “Consultancy services for Detail Engineering Design for Kurigram Irrigation Project (South Unit)” for Bangladesh Water Development Board/ Development Design Consultants Ltd. (DDC) in 2008-2009.
- Hydrologist of the “Impact Assessment of the proposed Indian River Linking Project for Inter Basin Water Transfer Project. Component 2: Environmental Support” for Water Resources Planning Organization (WARPO) during 2007-2008.
- Co-Author of the “Preparation of Medium Term Action Plan (MTAP) for the Chittagong Hill Tracts (CHT) for the year of 2008-12” for International Centre for Integrated Mountain Development (ICIMOD), Nepal in 2007.
- Water Resources Engineer of the “Chittagong Hill Tracts Natural Resources Management (CHARM)” for European Union-Asia Pro Eco, Component A, Diagnostic Activities (DIA) in 2005-2007.
- Junior Morphologist of “Predicting Riverbank Erosion along the Ganges and Padma Rivers for 2006” for Jamuna-Meghna River Erosion Mitigation Project (JMREMP), BWDB in 2006-2007.
- Junior Engineer of the “Preparation of Integrated Coastal Resources Database (ICRD)” for Water Resources Planning Organization (WARPO) during 2005-2006.

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The SENSE Research School declares that **Jakia Akter** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 36.8 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2014)
- Research in context activity: 'Co-organizing UNESCO-IHE PhD Symposium and Proceedings Booklet, Delft, 28-29 September 2015'

Other PhD and Advanced MSc Courses

- Academic English Writing, UNESCO-IHE (2014)
- Morphological modelling with Delft3D, UNESCO-IHE (2014)
- Summer school on estuarine and coastal processes in relation to coastal zone management, Netherlands Centre for Coastal Research (2015)
- Communicating Water – Bridging the gap between science and society, UNESCO-IHE (2015)

Management and Didactic Skills Training

- Event organizer and moderator of 36th IAHR World Congress 2015, The Hague, The Netherlands (2015)
- Event organizer for Second World Irrigation Forum 2016, Chiang Mai, Thailand (2016)
- Teaching in the MSc/PhD course course 'Morphological Modelling with Delft3D', Delft, The Netherlands (2015)
- Teaching the mid-level professionals training 'River and delta morphology: evolution, dynamics and prediction', Dhaka, Bangladesh (2016)

Oral Presentation

- *Assessing the rate of subsidence in the Bengal delta.* Deltas in times of climate change II, 24-26 September 2014, Rotterdam, The Netherlands

Poster Presentations

- *Decade to century scale geo-morphological development of Bangladesh*. PhD Symposium, Delft, The Netherlands (2014)
- *Prevailing processes in a tide dominated delta: Bangladesh perspective.* 36th IAHR World Congress, 27 June-3 July 2015, The Hague, The Netherlands

SENSE Coordinator PhD Education

Dr. Peter Vermeulen

The Ganges-Brahmaputra-Meghna (GBM) Delta is a good example of a large estuarine system with sparse data. This study describes the development and validation of a morphodynamic process-based model (Delft3D) as a tool to predict the dynamic system as a response to climate change, sea-level rise, subsidence and other influences. The modelled sediment transport of the Ganges and Jamuna systems is between 200 and 1100 million ton/year, which is in line with observations. On annual basis sand accounts for less than 20% of the sediment load in the system with the remaining sediment being much finer. Analysis of modelled bed level changes over time reveals that only a few river systems are in an aggrading phase. The 2D model exhibits that about 22% of the supplied sediment deposits in the delta system on floodplains and tidal plains, whereas the remaining 78% of the sediment causes subaquatic delta progradation or is lost in the deep ocean bed. Although the model does not reproduce all-natural phenomena at all spatial scales, it will be a valuable tool to describe and explore the morphodynamic development of the GBM Delta over decadal to centennial timescales for macro-scale understanding, planning, and management.

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