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Evolution of the Bengal Delta and Its Prevailing Processes

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ABSTRACT

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Bangladesh, occupying low-lying floodplains and tidal plains, has one of the largest and the most disaster-prone populous deltas in the world. The Bengal Delta is a tide-dominated delta, where tides play the key role in the sediment dispersal process and in shaping the delta. There are many studies and reports on river-dominated deltas, but research is sparse on tide-dominated deltas. The Ganges and Brahmaputra Rivers, which combined form one of the three largest riverine sources of water and sediment for the world's oceans, have developed the Bengal Delta to its present form with an aerial extent of 10^4 km^2. About 10^{12} m^3 of water with 10^9 tonnes of sediment per year make this system morphologically active. In the last five decades, the Bengal Delta has prograded at a rate of 17 km^2/y, whereas most large deltas elsewhere in the world suffered from sediment starvation. Delta progradation always makes the river system unstable, and rapid changes cause the delta to become dynamic. Sea level rise induced by unequivocal climate change and subsidence would make the delta more vulnerable in the coming decades. Although some literature is available on the millennium-scale development process of the Bengal Delta, sound knowledge on the decade- to century-scale processes of the delta development for facing the threats of climate change and deltaic subsidence is limited. In addition, there are significant differences in opinions and widely varying findings in the literature to the response of the delta to different natural and human interventions. Against this backdrop, relevant available literature on 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 a way into sustainable planning for this delta.

ADDITIONAL INDEX WORDS: *River shifting, delta progradation, sedimentation, subsidence.*

INTRODUCTION

The Bengal Delta is the largest delta in the world (Gupta, 2007). 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. These systems (Figure 1) carry the world's largest sediment load, more than 1 billion tonnes of sediment every year, of which nearly 80% is delivered during the four monsoon months (Goodbred and Kuehl, 2000b). Bangladesh, with more than 2% of the world's population and a density of more than 1080 people/km^2 (Steckler *et al.*, 2010), has a highly vulnerable coastal environment (Minar, Hossain, and Shamsuddin, 2013). Sea level rise (SLR) of 1 m would cause inundation of 17% to 21% of the total area of Bangladesh (Choudhury, Haque, and Quadir, 1997; IPCC, 2001). Because more than half of the area is less than 5 m above mean sea level, according to the digital elevation model, it could be more vulnerable for higher SLR and a high rate of subsidence. Differences in opinions are found in the literature on the impacts of climate change and subsidence. To address these impacts in the coming decades, it is necessary to review the varieties of ideas on different processes acting on the delta and seek to find some sustainable solution. Furthermore, many research studies have been carried out on river-dominated deltas, but few have focused on tide-dominated deltas, where tide plays the key role in shaping the delta. Even existing practices of delta models rarely include the interaction amongst rivers, floodplains, and tidal plains, because the processes in the delta system are complicated. Most delta models consider a static river system when they assess the long-term effects of climate change. Therefore, the related literature has been reviewed to outline the present understanding with a view towards finding knowledge gaps intending for further research.

STUDY AREA

This section describes the geological setting and the fluvial setting of the study area. In the geological setting, the main physical features that influence the development of the Bengal Delta have been figured out. Hydromorphological descriptions have been given in the fluvial setting section.

Geological Setting of the Study Area: Bengal Delta

Several million years ago, the NE portion of the Indo-Australian plate fractured and sank below what was then sea

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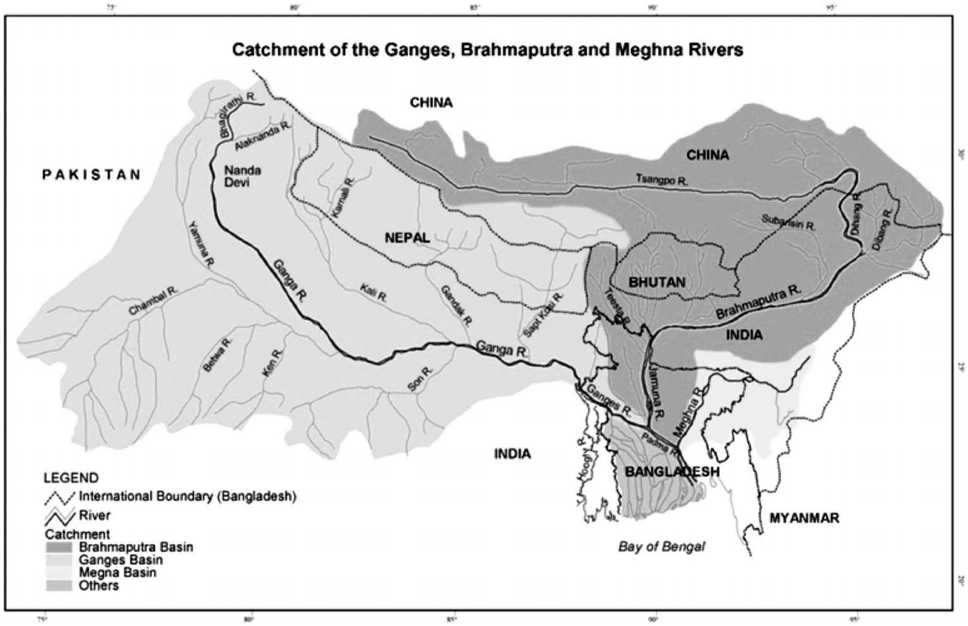

Figure 1. Location map of the Ganges, Brahmaputra, and Meghna catchments.

level. This depressed basin then attracted all rivers to meet the sea. In the course of time, this depression filled with the sediment to form the present Bengal Basin. The basin is prograding from a NE hinge line (Goodbred and Kuehl, 2000b). Deposition of 4 km of deposits at the hinge and more than 10 km at the shelf break (Lindsay, Holiday, and Hulbert, 1991) has made the world's largest fan deposits (Goodbred and Kuehl, 2000b), with a volume of approximately 1.25×10^7 km^3 for approximately 3×10^6 km^2 of area (Curray, 1994), mainly carried by the Ganges–Brahmaputra (G-B) Rivers from the foreslope and backslope of the Himalayas, respectively (Goodbred and Kuehl, 2000b).

Bangladesh occupies the major part of the basin (Figure 2). Geographically, the basin is the entire lowland, which is bounded by the Shillong Plateau on the north, the Burma Arc foldbelt on the east, the Bay of Bengal on the south, and the Indian craton on the west (Steckler *et al.*, 2010). The basin is separated from the Chittagong region by the Feni River. The geology of the Bengal Delta is mostly characterised by the uplifting of both the Himalayan mountains to the north and the frontal belt of the Indo-Burman Range to the east, tectonic subsidence, and refilling by rivers that has progressed towards the south. 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 course shifting or avulsion (Goodbred and Kuehl, 2000b).

Fluvial Setting of the Rivers in the Delta

Three large rivers, the Ganges, Brahmaputra, and Meghna, are the main fluvial sources of the basin (Figure 1). The Ganges River, with an average of 1200 mm of rainfall over about 1,000,000 km^2 of catchments, produces an annual average discharge of about 11,300 m^3/s, along with producing sediment at 550 million tonnes/y (CEGIS, 2010). The Brahmaputra River covers 573,000 km^2 with an average rainfall of 1900 mm, and it results in an annual average discharge of 20,200 m^3/s with 590 million tonnes/y sediment. A total of 1 trillion (10^{12}) m^3 of water and sediment at a rate of 1 billion (10^9) tonnes/y, 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. The hydromorphological details, including catchments areas and fluvial inputs of the different contributors to the basin, are given in Figure 3 for comparison. The sediment carried by the Ganges, Brahmaputra, and Meghna Rivers has contributed to the present size of the delta, which is about 100,000 km^2.

The average flood discharges of the Jamuna, Ganges, Padma (the main branches of the Ganges and Jamuna), and Upper Meghna Rivers are 70,000, 52,000, 95,000, and 13,700 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, Ganges, Padma, Upper Meghna, and Lower Meghna Rivers are 0.20, 0.15, 0.12, 0.14, and 0.09 mm, respectively. The planform of the rivers varies from meandering to braiding over space and time (the Jamuna is braided, the Ganges is meandering, and the Padma is a wandering river). The Upper Meghna is anastomosing, and the Lower Meghna is anabranching (Sarker *et al.*, 2003). Along with the sediment transported by these main rivers, the other two major

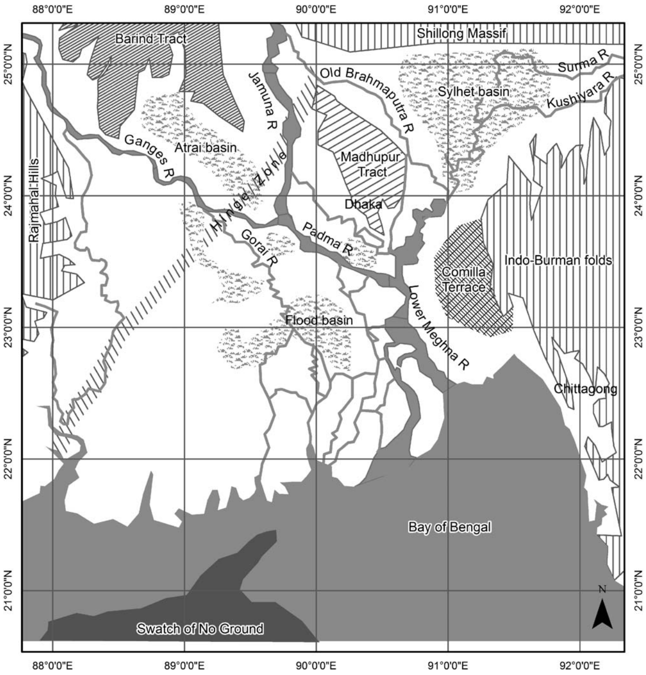

Figure 2. Geological setting of the Bengal Delta.

distributaries, the Gorai and the Arial Khan, contribute in transporting fluvial inputs to the delta system. The Gorai River delivers annually about 30 billion m^3 of water and 30 million tonnes of sediment to the bay (EGIS, 2001), and the Arial Khan River supplies about 30 billion m^3 of flow and 25 million tonnes of sediment every year. 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.

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 mesotidal estuary, where the tidal range varies between 2 and 4 m (MES II, 2001).

RESULTS

The process-based output from the literature review for establishing the geomorphological development of the Bengal Delta, especially the Bangladesh part, mainly addresses river and delta development since the Holocene on century and decade scales, including coastal morphology and erosion–accretion, subsidence, human interventions, impacts of climate change, and the role of extreme events such as the Assam earthquake of 1950 in delta development. Related discussions are given in subsequent sections.

Millennium-Scale Delta Evolution

Study of Bengal Delta development during the Holocene was carried out mainly by Allison *et al*. (2003), Fergusson (1863), Goodbred and Kuehl (2000a, b), Umitsu (1985, 1993), and Williams (1919). In addition, a few studies on the late Quaternary geology and landforms of the Ganges Delta were done by Morgan and McIntire (1959), and sedimentary processes and landforms along the Brahmaputra–Jamuna river system were discussed by Coleman (1969). Later, Umitsu (1985) classified landforms of the Bengal lowland using satellite images and described the evolution of the landforms during historic times. Umitsu (1993) clarified the characteristics of the late Quaternary sediments and sedimentary environments of the Ganges Delta based on soil test and grain size analysis in more than 300 columnar sections of boreholes in the Bengal Delta. But studies of detailed delta development from the late Quaternary through the Holocene were presented by Allison *et al*. (2003), Goodbred and Kuehl (2000a, b), and Kuehl *et al*. (2005) based on borehole data they collected themselves, along with data from Umitsu (1993) and other sources. Goodbred and Kuehl (2000b) developed palaeogeographic maps of the G-B Delta during the Holocene.

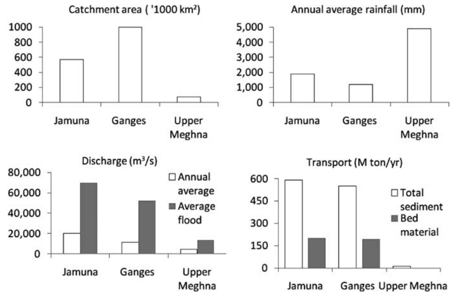

Figure 3. Hydromorphological characteristics of the three main rivers of Bangladesh.

Long-term shifting and recent shifting of the main rivers in this region were first described by Fergusson (1863) and Williams (1919), respectively, although their suggested time sequence could not be related to known changes in conditions bounding the terrestrial component of the delta, such as sea level changes. To address these limitations, Umitsu (1993) analysed data from 300 columnar boreholes within the Ganges Delta and the surrounding area using radiocarbon dating to develop palaeogeographic maps of the delta. Umitsu (1993) related changes in the courses of the G-B Rivers to rising sea level since its lowest stand during the last glacial maximum. While the sequence of shifting of the G-B Rivers suggested by Umitsu (1993) seems somewhat similar to that described by Williams (1919), the timing is different.

A comprehensive account of the development of the G-B Delta from the late Quaternary and extending through the Holocene was presented by Goodbred and Kuehl (1998, 2000a, b). Their account is based on borehole data they collected themselves, as well as that of Umitsu (1993) and other sources. Based on the compiled data, they presented palaeogeographic maps of the development of the G-B Delta. They concluded that changes to the courses of the G-B Rivers were a consequence of the delta building process, which was itself driven by abundant sediment input from erosion of the Himalayas, conditioned by sustained SLR that began during the late Quaternary and modified internally by regional tectonics within the Bengal Basin. The palaeogeographic maps of Goodbred and Kuehl (2000b) are more detailed than those of Umitsu (1993) and represent the most up-to-date account of how the configuration of the major rivers (Figure 4A) has evolved to its current pattern.

In line with the descriptions of Goodbred and Kuehl (2000b), Allison *et al*. (2003) have also given five timings of the phases (Figure 4B) of late Holocene growth of the lower delta plain associated with the Ganges (G1, G2, G3), the Brahmaputra (B1, B2), and the combined G-B Rivers (GB1), though there are some dissimilarities of timescales. Goodbred and Kuehl (2000a) have also shown a deltaic silt deposit up to 60 m thick within the Holocene sediment discharge of the G-B Rivers over an oxidised low-stand surface (exposed 10,000–11,000 years before present). Hence, basin filling was done by alternate sequential sediment carried by the G-B Rivers through their avulsion and migration process and its consequences. In the central Sylhet Basin, thick, fine-grained sequences indicate long-term flood basin deposition fed by episodic Brahmaputra-driven sediment input. The results show increasing distance from the fluvial sediment source and the thickest 80 m Holocene sediments in the subsiding northern basin. The time span for Brahmaputra avulsion to and from eastern and western sides of the Madhupur Tract is about 2000 to 3000 years. The last avulsion of the Brahmaputra from the east to the west along the Jamuna course started following an earthquake in 1782 and major flood in 1787 (Allison *et al*., 2003).

It may be concluded that the modern G-B Delta began to develop during the late Quaternary and before the Holocene, although the major part of its development occurred during the Holocene. Within this period, the Ganges shifted incrementally from west to east, primarily, as a consequence of the delta building process conditioned by the effects of SLR. Conversely, the Brahmaputra switched back and forth from the east of the Madhupur block to the west, featuring periods of extensive delta building interspersed with episodes of rapid inland deposition and fan building as a result of sedimentation within the Sylhet Basin. This behavioural aspect may be explained as the result of coupling of the delta building process with SLR, as modified by the effects of tectonic subsidence of the Sylhet Basin.

Century-Scale Delta Development

The major change in the last two centuries was the Brahmaputra avulsion, although many other changes in other river systems were the result of response and adjustment of the avulsion. The last shifting of the Brahmaputra, from the east of the Madhupur Tract to the present course of the Jamuna River, occurred between 1776 and 1830. Thus, the shifting process was not a sudden phenomenon; it took more than 50 years (Hirst, 1916). Based on Rennell's map (published in 1776), where the Brahmaputra is seen flowing along the present course of the Old Brahmaputra River at the east of the Madhupur Tract, Sarker (2009) mentioned that the shifting of the main courses of the river began after 1770. As found in the Colonel Wilcox's map of 1830, Sarker (2009) also mentioned that the shifting process was accomplished by 1830.

Buchanan Hamilton mentioned in 1810 that the Brahmaputra was threatening to shift westwards along the course of Konni (or Jennai) River at that time (Fergusson, 1863). The threat started to take effect in the late 18th century, taking many years according to many studies, and finally the Brahmaputra started to divert the flow through the Jennai River (Coleman, 1969; Morgan and McIntire, 1959; Sarker, 2009). However, based on Rennell's map of 1776 and modern maps, Bristow (1999) argued that the Jennai River was located to the east of the town of Dewanganj (in the Jamalpur district) before the avulsion but that after the avulsion the Brahmaputra occupied a channel west of Dewanganj.

Goodbred and Kuehl (2000b) mentioned that the most recent avulsion was the latest phenomenon within a series of periodic switches of the Brahmaputra, mainly related to the delta building process, from the east to the west of the Madhupur Tract between 200 and 300 years ago. Although different events may act as triggers for particular avulsion events, tectonic uplifting and tilting of the Madhupur Tract and associated subsidence in the Sylhet Basin would be the underlying cause of switching. Other triggering events might be earthquakes, tributary diversions, and major floods. The crossing of geomorphic thresholds intrinsic to the fluvial system could be another triggering event (Schumm, 1977) that may be associated with channel slope adjustment processes driven by sediment accumulation. Alternately, this could be centred in the Sylhet Basin and the trough between the Madhupur and the Barind Tracts.

This change in a large system caused several other changes to the river systems. After the process of avulsion of the Brahmaputra River to the Jamuna River had started, the course of the Jamuna and Ganges received increasingly more flow. The Center for Environmental and Geographic Information Services (CEGIS, 2011) mentioned that a small channel named the Kirtinasha River was created from the Ganges to the Meghna River and that the main flow of the Ganges River was diverted through the Kirtinasha River to the Meghna River. Subsequently, the Arial Khan, the old course of the Ganges River, became the right bank distributary of the Ganges–Padma river complex (CEGIS, 2011). Earlier, the Ganges abandoned its former courses while leaving a right bank distributary as it shifted eastwards, such as the Hoogly and Gorai Rivers (Williams, 1919).

When the main flow of the Ganges was flowing into the present course of the Gorai River, the western part of the Bengal Delta was receiving sediment to be developed. The eastern delta was supported by the Brahmaputra River–driven sediment. Presently, the combined flow of the G-B Rivers is prograding the eastern part of the delta (active delta), rendering the western part as a moribund delta and implicating erosion as the governing process.

At first, the possibility of the delta shifting from its easternmost part of the basin to the west was indicated by the Food and Agriculture Organization (FAO, 1988). In last 200 years, many changes, mainly to distributaries of the Ganges, the Padma, and the Lower Meghna Rivers, have been experienced in the SW region of Bangladesh (Figure 5). At

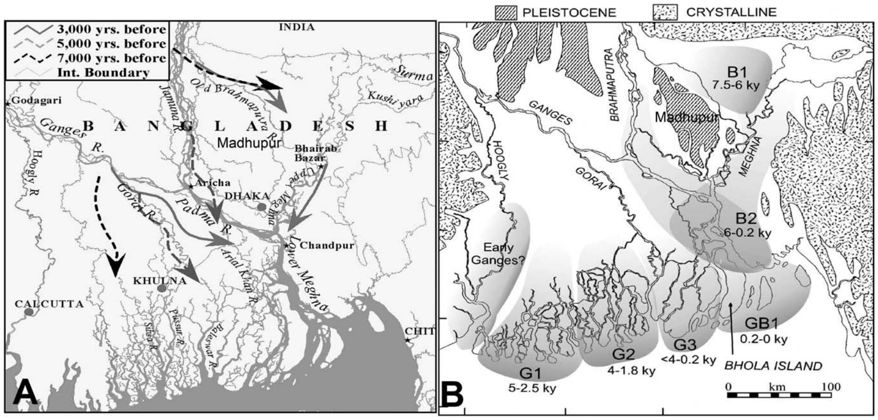

Figure 4. (A) Shifting of the G-B Rivers from the palaeogeographic map. (B) Pathways and the timing of phases. (Source: Sarker, Akter, and Rahman, 2013)

present, most distributaries have changed their flow direction towards the S and SW.

In the late 18th century, the Ganges and the combined flow of the Brahmaputra and Meghna were active in two separate estuaries for building the delta (Sarker, Akter, and Rahman, 2013). The Ganges estuary was close to the northern upstream reach of the Tentulia Channel, and the Lower Meghna River was delivering fluvial inputs to an area further east of the present active estuary. After joining of the Brahmaputra, enormous changes occurred in the following decades. The active delta building estuary shifted towards the east, and the process continued until the middle of the 20th century. The easternmost channel of the Lower Meghna estuary has been abandoned, resulting in the initiation of reverse shifting of the active delta building estuary towards the west. Based on analyses of satellite images, hydrographic survey charts, and field measurements, Sarker, Akter, and Rahman (2013) showed that many of the distributaries of Meghna, Arial Khan, and Gorai Rivers have been widening and deepening, resulting in increasing conveyance area.

Delta progradation, shifting of the delta building estuary, and shifting of the direction of the distributaries are the indicators for recognising delta shifting, even though these indicators are qualitative. According to Sarker *et al*. (2011) and Sarker, Akter, and Rahman (2013), huge accretion in the 1950s and 1960s caused delta progradation and thus expedited the shifting process. They also indicated the role of the 1950 Assam earthquake in expediting the shifting process. The changing of processes during recent centuries and decades indicate that the shifting process will continue in the coming decades.

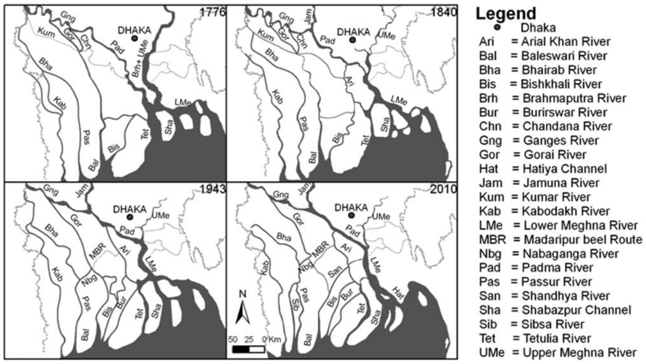

Figure 5. Development of the main rivers in Bangladesh over time (Source: Sarker, Akter, and Rahman, 2013).

Decade-Scale Delta Development

During the last few decades, several changes occurred in the distributaries. Some of them have been recognised, and some of them are yet to come onto the scene. The causes of these changes could be both anthropogenic and natural. Many artificial changes have been made in this region during 20th century. In the western part of the delta, the Gorai River has diverted 50% to 95% of its flow to its SW-directed distributary, the Nabaganga River (EGIS, 2001). CEGIS (2012) mentioned that before the construction of the Madaripur Beel Route (MBR) in the early 1900s, the main flow of the Gorai-Madhumati River was moving to the Baleswar River and the Nabaganga River discharged into the Rupsha–Passur system. Early in the 19th century, a small link canal, the Helifex cut, was created near Bardia, about 20 km upstream of the MBR confluence with Gorai-Madhumati River, and then the main flow of the Gorai-Madhumati River gradually shifted to the Nabaganga River and finally met the Passur system through the Atai and Rupsha Rivers. At present, more than 90% of the flow of the Gorai-Madhumati River runs through the Nabaganga River. Downstream of the Bardia, the Atharbanki River (a seasonal connection) exits from the Gorai-Madhumati River (Manikdaha) and joins the Rupsha River. A small percentage of the combined flows of the Gorai-Madhumati River and the MBR presently move into the Baleswar River through the Kaliganga and Kacha Rivers. Because the depth of the Passur system is higher than that of the Baleswar system, the tide comes earlier through the Passur system. CEGIS (2012) rationalised that although the Baleswar River carries freshwater, the early flow of the tide from the Passur system

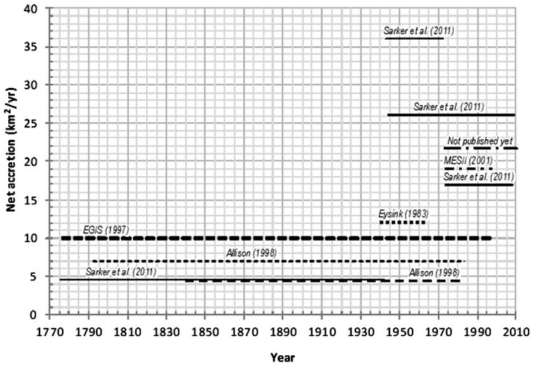

Figure 6. Net accretion rates by different studies. Decade-scale studies indicate the rates vary from 17 to 36 m/y, and rates from century-scale studies vary from 4.4 to 9.9 m/y.

through the Rupsha–Atai–Nabaganga system brings saline water downstream of the MBR. Likewise, the Nabaganga River's many distributaries generated SW from the Lower Meghna and Arial Khan Rivers are becoming enlarged in terms of depth and width (Sarker, Akter, and Rahman, 2013), and the Shandhya is a newly developed river in the SW region of Bangladesh that became visible in a 1973 image.

Coastal Morphology and Erosion–Accretion Processes

Allison (1998), Environmental and Geographic Information Services (EGIS, 1997), Eysink (1983), the Meghna Estuary Study (MES II, 2001), and Sarker *et al*. (2011) have studied erosion and accretion in the coastal region of Bangladesh. The study periods varied from a few years to several centuries; thus, the rates of change vary significantly. The century- to decade-scale erosion–accretion estimations were carried out mainly based on available historical maps. A summary is shown in Figure 6. Results from map analyses in different studies show that the century-scale net accretion rates, from the late 18th to the late 20th century, vary from 4.4 to 9.9 m/y, whereas the decade-scale net accretion rates vary from 17 to 36 m/y. Significant human interventions in the coastal area like cross-dams, along with estuarine-favourable conditions, have contributed to a huge land reclamation process (Figure 7).

Based on analysis of two satellite images from 1973 and 2008 (Sarker *et al*., 2011), the most sediment deposition–prone area in the Meghna estuary is the Noakhali district, which is almost the eastern boundary of the delta, as shown in Figure 7. In other districts, however, the land erosion was almost balanced by the land accretion. Sarker *et al*. (2011) mentioned that the tidal circulation is the main driving process contributing to the net land formation.

Recently, Rahman, Dragoni, and El-Masri (2011) investigated the coastal erosion along the Sundarbans (both Bangladesh and India), which is the westernmost coastal boundary of the delta, using time series satellite images from 1973 to 2010. They found that erosion is the dominating process along the coast of the Sundarbans. The average annual rate of accretion during the last 37 years was 4.8 km^2/y. Recognising that net accretion is the dominating processes along the Bangladesh coast, Rahman, Dragoni, and El-Masri (2011) mentioned that because of lack of sediment supply, along with SLR, the coast along the Sundarbans is experiencing an erosion phase.

However, satellite image analyses of 1973 and 2010 reveal that net erosion prevails along the total Sundarbans coastal area both in Bangladesh and India (Figure 8). However, net accretion is found in the Hoogly River estuary and in the presently active coastal part of the Meghna estuary. This part of 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. The comparison of yearly images suggests that net accretion in the Meghna estuary area is about 790 km^2. This indicates that yearly net accretion is more than 21 km^2. It is notable that the flow to the Hoogly River is not natural. It has been achieved by diverting Ganges water after construction of the Farakka Barrage in India during the mid-1970s.

Sediment Distribution Process in the Active Delta Building Estuary

After a consecutive sequence of active estuary shifting, such as the Hoogly, Gorai, and Arial Khan, the present active delta building estuary is the Meghna estuary. Almost all flow and sediment are presently passing through the Meghna estuary. Therefore, to understand the future development of the delta, we must understand the past and present formation of the estuary. The sediment distribution process in the active

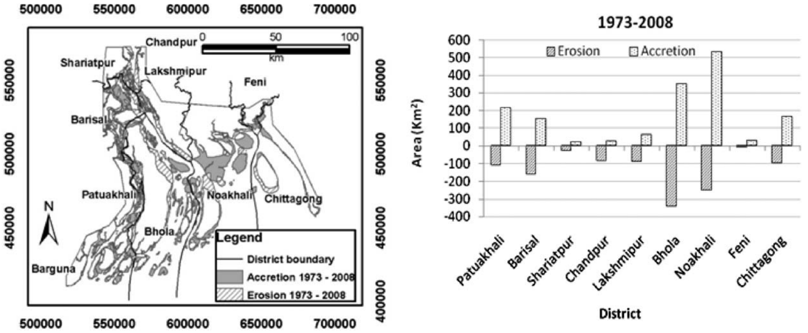

Figure 7. Erosion and accretion in different coastal districts adjacent to the Meghna estuary (1973–2008).

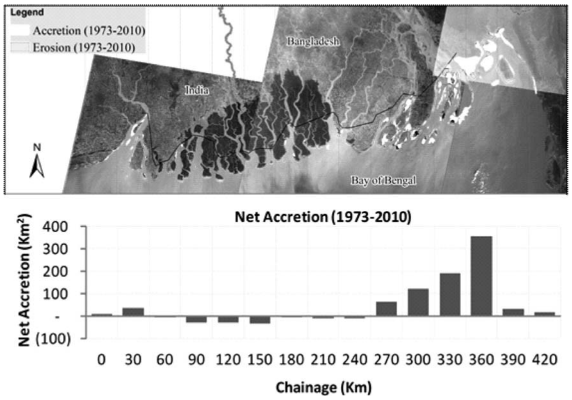

Figure 8. Net accretion rates in the coastal boundary of the Bengal Basin between 1973 and 2010. Positive indicates net accretion and negative indicates the net erosion.

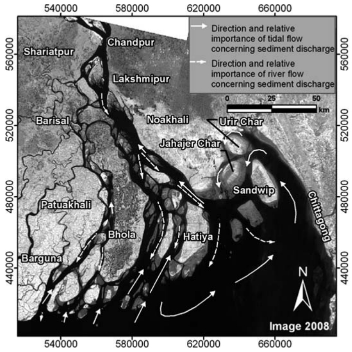

Figure 9. Sediment circulation processes in the Meghna estuary (Source: Sarker *et al.*, 2011).

estuary is responsible for reclaiming land in some favourable condition. The complex interaction between fluvial and tidal flow, along with waves, influences the morphology of the estuary. Every year, the estuary receives more than 1 billion tonnes of sediment with 1 trillion m^3 of flow from 92% of the catchments in Bhutan, Nepal, China, and India. The flow and sediment finally meet the sea through three major distributary systems: the Tentulia, Shahbajpur, and Hatiya Channels (Figure 9). The sediment discharge from the Lower Meghna River is the third highest (Milliman and Syvitski, 1992) and the water discharge is the fourth highest (Milliman, 1991) of all river systems in the world. The volumetric quantity of flow and sediment could well be visualised by 7 m of water and 3.5 mm of sediment column spread over the land of Bangladesh (147,570 km^2).

Although the Hatiya Channel was active a few decades ago, after development of the eastern part the fluvial process in the Shahbajpur Channel has become more active than the tidal process. Even the flow distribution processes change rapidly amongst the channels in this dynamic estuary (Sokolewicz and Louters, 2007). The sizes and shapes of several large islands (Bhola, Hatiya, and Sandwip) and their locations in the estuary play the key role in distributing the flow and sediment (Sarker *et al.*, 2011). Figure 9 shows the sediment circulation processes in the Meghna estuary, as described in MES II studies, based on measurements and modelling exercises. The circulation process is important for horizontal and vertical land development when sediment and tidal asymmetry occur.

The formation of the delta morphology and planform are complexly controlled by river discharge, tidal range, and wave energy flux (Galloway, 1975; Nienhuis *et al.*, 2012), although there are other influencing factors, such as grain size distribution (Orton and Reading, 1993), (relative) SLR (Giosan *et al.*, 2006), human engineering (Syvitski *et al.*, 2009), sediment cohesion (Edmonds and Slingerland, 2010), and angular distribution of wave energy (Ashton and Giosan, 2011). The river-dominated Mississippi Delta is formed by developing delta lobes like the foot of a bird (Seybold *et al.*, 2009). In bird-foot deltas, rivers have higher energy than that of waves and tides. On the contrary, the formation of estuaries with high tidal energy demonstrates distributary funnel-shaped channels with linear river-mouth bars (Fookes, Lee, and Griffiths, 2007), such as the Meghna estuary. In a river-dominated delta, sediment deposition occurs by river flushing, whereas the river carries sediment that is then redistributed by the tides (Hori and Saito, 2007) in the tide-dominated deltas.

The ratio of the distribution of freshwater has yearly seasonal variation and occurs over a period of decades, depending on the channel developing processes, in the Meghna estuary. According to MES II (2001), the monsoon flow distributions in the Tentulia, Hatiya, and Shahbajpur Channels are 15%, 10%, and 75%, respectively. The bed material of the channels is fine sand and silt with grain size varying from 0.016 to 0.25 mm. The fine fractions of the sediment control the sediment reworking process (Sokolewicz and Louters, 2007). The magnitude of the maximum suspended sediment concentration at the NE part of the Meghna estuary in the Sandwip Channel was found to be 9000 ppm with a flow velocity of 4 m/s, indicating the dynamism of the estuarine environment.

The sediment characteristics, tidal range and characteristics, waves, and planform of the estuary are the main governing processes in distributing the sediment (Bird, 2008; Palinkas, Nittrouer, and Walsh, 2006). The monsoon flow's sediment input into the estuary is 20 to 30 times higher than that of the dry seasonal flow; however, most sediment enters the estuary during monsoon (Sarker *et al.*, 2011). The lower limit of the Shahbajpur Channel is seen to be the turbidity maximum, where a finer fraction of the sediment takes up temporary residence (Sokolewicz and Louters, 2007). Sediment concentrations at turbidity maximum locations, which generally occur in the low salinity zone and shift location with flood discharge changes (Grabemann, Kappenberg, and Krause, 1995), are as high as about 2000 ppm (MES II, 2001). The location of the turbidity maximum moves back and forth with the tide, causing fine sediment movement before its final deposition. The temporary storage of fine sediment during the monsoon is the zone of the turbidity maximum, which is the main source of sediment redistribution during the dry season (Sarker *et al.*, 2011). However, dry season sediment supply is insignificant in comparison to that of the monsoon season, except in the NE zone of the tide-dominated Meghna estuary. No significant seasonal variation was found in this zone (IWM, 2010).

Sedimentation in the estuary depends on the relative strength of the flood and ebb tide in the channels (Bird, 2008). During monsoon, the high flow velocity generally transports sediment to the shallow intertidal area by a tidal pumping process; then, the sediment is dispersed to the NE part of the estuary by a tidal circulation process. Mathematical modelling, along with field observation, showed that the freshwater flow to the Shahbajpur and Hatiya Channels forms loop circulations around the islands Sandwip, Urir Char, and Jahajer Char (MES II, 2001). High sediment input from upstream and high tidal energy from downstream make the estuary dynamic. Thus, the estuary has been characterised by several thousand square kilometres of land erosion accretion every year. Erosion in channels mainly occurs by shifting and widening, whereas around islands it occurs by retrenchment. However, accretion occurs by the formation of the mainland towards the sea and the extension and improvement of islands.

Recent research from CEGIS (2010) indicates that in the Meghna estuary, the dispersal process of the fine-sand fraction of sediment is different from that of silt and clay. The ratio of fine sand to silt and clay coming through the rivers is 1:4. Preliminary findings of research from CEGIS (2010) showed that when more of the coarse fraction of the sediment with fine sand was in the Meghna estuary during the mid-1980s and mid-1990s, the net accretion was very high in the Bhola and Patuakhali districts. But in other decades (between the 1950s and the 2010s), when the coarse fraction was lower and the fine fraction (silt and clay) was higher, the net accretion was significantly higher in the Noakhali district. This indicates the roles of fine sand and of silt and clay in reclaiming land in the estuaries. Further research on this issue could help to mitigate erosion in the western part of the delta in different scenarios of sediment change through intervention and land-use management in the catchments.

Subsidence in the Bengal Delta

Deltas are naturally dynamic coastal systems that are unique in their close links to both land-based fluvial and coastal ocean processes. Subsidence of unconsolidated deltaic sediments is a natural process occurring constantly in deltas as a result of natural and anthropogenic processes of different scales. Natural subsidence occurs largely as a result of compaction of deltaic deposits (van Asselen, Stouthamer, and van Asch, 2009), tectonics, and isostasy (Kooi *et al*., 1998). Moreover, most deltas overlie deeply buried deposits that are gradually subsiding by compaction. Natural subsidence rates in deltas is slow, generally ranging from less than 1 to more than 10 mm/y (Jelgersma, 1996; Stanley and Warne, 1998), whereas anthropogenic activities, such as groundwater or gas extraction, cause rapid subsidence on a several-centimetre scale. The rapid subsidence rate varies from 22 cm/y in western Indonesia (Chaussard *et al*., 2013) to tens of centimetres per year in Mexico City and Las Vegas (Bell *et al*., 2002; Cabral-Cano *et al*., 2008). However, compaction because of anthropogenic activities may accelerate the natural subsidence. If the subsidence rate is greater than the global sea level rise (GSLR), then it has an impact on socioenvironmental issues. Misconceptions about land subsidence have significantly affected coastal development. In many cases, relative sea level rise (RSLR) includes subsidence and GSLR. Hence, subsidence in any delta can be found directly from RSLR, because GSLR is already known.

Accurate measurements of subsidence within deltas are rare. The subsidence measurement procedure mainly depends on the country's economic condition and the importance of the area. Traditional measurements of land subsidence using GPS and levelling data are location specific and may not reflect the actual condition. They are also highly time consuming and costly. Presently, by using InSAR, a powerful new synthetic aperture radar mapping tool, many developed countries are monitoring land subsidence in many metropolitan areas, such as Las Vegas, Mexico City, Paris, Naples, Venice, Lisbon, and Shanghai (Chaussard *et al*., 2013). But subsidence rate calculation in Bangladesh so far has been mainly based on satellite image and borehole data analysis. Comparing the carbon-dating year of borehole samples with the GSLR has been the basis for subsidence rate measurement in the recent years.

Church and Gregory (2001) mentioned that GSLR rose slowly during the last 3000 years until rates apparently began to increase during the middle of the 19th century. It is widely believed that GSLR could accelerate during the 21st century, primarily because of warming of the global climate and the associated thermal expansion of oceans and melting of the Greenland and Antarctic ice caps and glaciers. They attribute the GSLR to changes in mass of the oceans (*i.e*. the addition of glacial meltwater), along with the effects on the world's oceans (*i.e*. thermal expansion and salinity changes). Miller and Douglas (2004) estimated that the GSLR during the 20th century typically ranged between 1.5 and 2 mm/y. Today, the GSLR is positive and contributes around 1.8 to 3 mm/y under the anthropogenic influence of global warming (Church and White, 2006; Syvitski *et al*., 2009).

Like the NE region of Bangladesh, called the Sylhet Basin, the SW part is experiencing subsidence, though only to a limited extent, by groundwater abstraction (not gas abstraction) in a few urban areas such as Khulna. In addition, sediments carried through during Holocene, Pleistocene, and Tertiary have contributed to form much of the Ganges Delta. Because most of the sediment is sandy (Zahid and Ahmed, 2006), it is not susceptible to compaction by water abstraction. Moreover, Holocene peat layers underlying large parts of the tidal floodplain have remained saturated since their formation and so have not shrunk by drying out—except locally, where water has been abstracted for city dwellers under Khulna City Corporation. Hence, the cause of subsidence in this region is tectonic movement or faulting in the Bengal Basin within which the region lies, possibly complicated by folds and faults within the basin (Stanley and Hait, 2000; Steckler, Akhter, and Seeber, 2008).

Previous studies have shown that significant subsidence or a RSLR has taken place over the entire Holocene based on sediment accumulation rates of 1 to 4 mm/y for the eastern Sundarbans outer delta plain (Allison and Kepple, 2001) and no more than 5 mm/y for the western Sundarbans (Stanley and Hait, 2000). Morgan and McIntire (1959) found subsidence of

3.7 to 6.7 m in the Sundarbans area and 6.1 m in Sekhertek near the Sibsha River through shallow auger boring, though they did not mention any duration to calculate the rate of subsidence. Likewise, the subsidence rate in the Sundarbans, which is unintervened, is 1.3 to 7.1 mm/y, based on calculation of depths to radiocarbon-dated organic materials (Allison *et al.*, 2003; Brammer, 2014). However, based on radiocarbon dating of wood, peat, and shale, Umitsu (1993) stated that the coastal areas of Bangladesh are subsiding at a rate of about 3 mm/y.

Mikhailov and Dotsenko (2007) reported that the RSLR in the sea exposed part of this delta is 10 to 20 mm/y. Ericson *et al.* (2006) also reported that the subsidence rate, as high as 25 mm/y, results partially from groundwater extraction through shallow and deep tube wells (Alam, 1996; Haq, 1997). Though subsidence rates in excess of 25 mm/y might not be acceptable (Nicholls and Goodbred, 2005), many studies have reported such a magnitude mainly based on artefacts and tree stumps that are buried in the lower coastal plain. The uncertainty of carbon dating and location of artefacts is very high, which may run the risk of producing unattainable results of short-term to long-term subsidence rates. If there were such subsidence, rapid sedimentation would balance the vertical land loss. No place in this area has, until now, been reported as a hotspot of land loss. For such a huge sediment rate, enhanced flooding could also be reported.

A recent study by Syvitski *et al.* (2009) on subsidence has made scientists and decision makers to pay more attention. The study authors estimated the rate of RSLR for the different deltas in the world. They used Shuttle Radar Topography Mission data to relate the topography of the delta with mean sea level; historical maps to know the river shifting; Moderate-Resolution Imaging Spectroradiometer satellite images to establish the extent (on the delta) of flooding and their sources, from river runoff or from coastal storm surges; and the presence of suspended sediment in the floodwaters. They also tried to determine whether the deltas are developing with the SLR by adding new sediment layers to their surface during periods of flooding. They claimed that the Bengal Delta was sinking at a very high rate of 8 to 18 mm/y. The Bengal Delta was amongst their 33 'sinking deltas' worldwide, and they argued that these deltas were experiencing large subsidence rates attributed to human activities such as embankment construction and water or gas abstraction. Their results, however, are not supported by the ground truths. The Ganges Delta includes the Ganges River floodplain, not just the tidal floodplain assumed by the authors, and there is no field evidence that either of these regions is subsiding at such a high rate. However, subsidence rates are not uniform within the area.

Hanebuth *et al.* (2013) has also given some sinking rates based on the position of 20 kiln bases in the Sundarbans in relation to winter and spring high-tide levels. Based on the elevations and ages (found by optically simulated luminescence dating), the 300-y average rate of sinking of the outer delta is 5.2 ± 1.2 mm/y, which includes 0.8 mm/y of eustatic sea level rise (ESLR).

Sarker *et al.* (2012) showed that the long-term subsidence rate in the tidal plain of the Bengal Delta has not exceeded 1 to 2.5 mm/y, based on measurements of plinth levels of a 15th-century mosque at Bagerhat situated in the north of the tidal floodplain, a 400-year-old Hindu temple in the Sundarbans forest in the south, and a 200-year-old temple 25 km NE of Khepupara in the SE. If subsidence had occurred at a rate of up to 18 mm/y, as suggested by Syvitski *et al.* (2009), those monuments would have been 2.4 to 7.5 m below tidal plain or forest floor, which did not happened.

Pethick and Orford (2013) showed substantial relative mean sea level (RMSL) ranges from 2.8 to 8.8 mm/y in SW estuaries in Bangladesh based on three sets of tidal water-level data analyses in the Passur system, covering the uninhabited Sundarbans Reserve Forest (SRF), the junction between the SRF and the extensive polder area northwards, and the densely populated Sundarbans impact zone. They have shown the causes of increasing trends in high water maxima to result from a combination of deltaic subsidence, including sediment compaction, and ESLR; they recognised the principal cause of the increasing trend to be increased tidal range in estuary channels recently constricted by embankments. They found that the increase in RMSL in the Sundarbans is significantly greater than the increase in mean sea level. Freshwater discharge into the system is another cause for increase in high water maxima.

In summary, studies carried out so far recognised that there is deltaic subsidence in the south-central and SW part of the country. Sedimentation is compensating for this subsidence outside the polder area. It can be said that subsidence in the delta area has altered the natural shape of the delta, especially after the polderisation. There are differences of opinions on the rate of subsidence, ranging from a few millimetres to a few centimetres per year, which need to be resolved for long-term planning. To substantiate an acceptable rate of subsidence, further research is needed on this aspect.

Human Interventions

Rivers have nurtured civilisation throughout human history (Hefny and Amer, 2005). The Nile River allowed Egypt, known as one of the oldest agricultural civilisations and a sedentary agricultural society, to develop thousands of years ago. The Nile River and its delta have been altered by anthropogenic intervention that has turned a prograding delta to an eroding coastal plain (Stanley, 1996). The agricultural-based civilisation was initiated based on the fertile lands of delta and tidal plains. Similarly, to produce more food from floodplains and tidal plains and to make social life safer, the people of Bangladesh started to intervene in the natural systems in primitive ages. Those early interventions in the delta could not negatively affect the natural system, because they were not significant in terms of altering the flow and sediment regime. Over the centuries people made earthen dykes with their limited efforts to protect their homes and homesteads from tide and salinity intrusion. However, during the last century, large-scale interventions in the river systems have been made in the SW region of Bangladesh to improve communication networks, increase agricultural production, and enhance safety in the coastal environment.

In the first half of the 20th century, during the British regime, several alterations were made to maintain or improve the navigation in the riverine delta—at that time the main

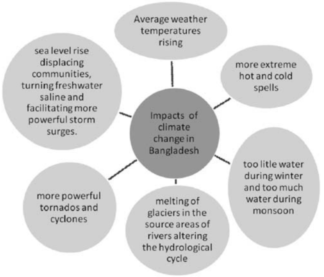

Figure 10. Impacts of climate change in Bangladesh.

mode of transporting goods and passengers. The British connected different rivers such as the Gorai-Madhumati with the Nabaganga at the beginning of the 20th century and excavated canals such as the Heliflax cut, MBR, Gabkhan Canal, and Mongla-Ghashiakhali Canal. The Heliflax cut, made in 1910 to shorten the distance from Dhaka to Khulna, connected the Madhumati River with the Nabaganga River. As a consequence, a significant amount of flow of the Madhumati River started to be diverted through the Nabaganga River. After excavation of the 23-km MBR during 1910–12, part of the Arial Khan River flowed into the Madhumati River. Gabkhan Channel was excavated in 1918 to connect the Shandhya River of the Pirojpur district and the Sugandha River of the Jhalakati district with a view towards reducing the navigation distance by around 118 km. Several other modifications to river courses were made in early 20th century during the British regime. Then the Bangladesh Inland Water Transport Authority excavated the Mongla-Ghashiakhali Canal, which was opened for navigation in 1974, to reduce navigation distance. All these connections modified the flow and sediment in the SW region of Bangladesh. Other additions, such as construction of railways and highways transversely crossing the flood plain, also restricted free flow of floods over the terrain.

In the second half of the 20th century, changes in the delta plain and in the catchments upstream of the delta were enormous. Several flood embankments and polders were constructed in the floodplain and tidal plains of Bangladesh in the 1960s and 1970s, aiming to protect flood and grow more food by improving water management, on the basis of the recommendations from the master plan for what was then the East Pakistan Water and Power Development Authority (EPWAPDA), prepared by the International Engineering Company of San Francisco in 1964. Those coastal polders limited the flooding on the tidal plains by restricting the tide from entering the tidal plain. After construction of the polders under flood control and irrigation projects, people initially benefited. However, after coastal embankment projects, especially in the SW region of Bangladesh, the adverse effects were enormous. Several tidal channels died within a few years to a few decades, drainage congestion become severe in many of the embanked polders even as tidal amplification increased flooding of the unintervened tidal plains, and riverbed sedimentation deteriorated the navigability of many important navigation routes. The tidal amplification could sometimes be disastrous, such as seen in the effects of the cyclone Aila (2009) in the SW. These are common features in the Satkhira, Jessore, Khulna, and Bagerhat districts. Different studies found that tidal amplification and sedimentations in the riverbed occurred because the tidal prism was cut down by the coastal embankment. The tidal river management concept (creating a tidal basin for an increasing tidal prism in the tidal channels; EGIS, 1998) has become popular, although numerous constraints in the implementation process exist. Moreover, the Bangladesh Water Development Board has recently been working to improve coastal embankment projects, considering an expected SLR of 0.5 m over the next 50 years and subsidence 12 mm/y.

Other than the internal human-induced changes, intensive agricultural practices, such as deforestation, and construction of dams and barrages for storing and diverting water in the catchment of the G-B Rivers, such as Farakka Barrage on the Ganges, occurred beyond the international border (Mirza, 2004; Mirza and Sarker, 2005; Sarker, 2004). Those interventions have also contributed to change the flood, sediment, and dry season flow regimes of Bangladesh. Low flow during dry season causes an increase in salinity intrusion further upstream. Therefore, manmade changes both within and outside the country and ongoing natural processes are acting on this delta, along with continuous adjusting and combating of SLR and changed sediment and flow conditions.

Impact of Climate Change

A few places in the world are vulnerable to the effects and severity of climate change; amongst them, Bangladesh will likely be one of the most experienced countries (Ahmed, 2006; Pender, 2008). Global warming, along with RSLR, is expected to cause significant changes in the flood regime (Climate Change Cell, 2006; Mirza, 2002, 2003; WARPO, 2005; Yu *et al.*, 2010). The impacts of climate change in Bangladesh could be as shown in Figure 10, according to Pender (2008). Moreover, seismic events in the Brahmaputra Basin (Goodbred *et al.*, 2003) could change the sediment scenario and its responses. Any of these single or combined factors in the river catchments would change the flow and sediment regime of the river and the estuary. A period of fluvial process and morphological form adjustments would make the system 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. 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.

Choudhury, Haque, and Quadir (1997); the Climate Change Cell (2006); the International Panel on Climate Change (IPCC, 2001); the Institute of Water Modelling (IWM, 2008); the Water Resources Planning Organization (WARPO, 2005); Yu *et al.* (2010); and many others have carried out studies addressing the changing flooding and inundation pattern in Bangladesh because of climate change. Though the process of fluvial adjustment with climate change is not well understood, it presents complicated and challenging issues (Goudie, 2006; Macklin and Lewin, 1997). Blum and Törnqvist (2000), Fisk (1994), Mertes and Dune (2007), and Muto (2001) have studied fluvial adjustment to climate changes. Those studies do not address short-term adjustment processes on timescales of decades to centuries. However, the process of understanding the responses of rivers and estuaries to climate change is imperative for fixing a strategy for adaptation to climate change—especially for a country like Bangladesh, where the delta is enormous, the rivers are dynamic, and the river adjustment processes play an important role in flooding, inundation, and riverbank erosion.

Increase of temperature in the earth system is the main factor for climate change. Choudhury, Haque, and Quadir (1997) did not find significant changes in the temperature and rainfall data from 1960s to 1993 in Bangladesh and concluded that three decades are not sufficient for determining a long-term trend. However, they mentioned that rainfall might increase with an increase of temperature, in accordance with the IPCC's 1990 business-as-usual scenario (Tegart, Sheldon, and Griffiths, 1990). If the rainfall increases, river discharge will also increase, though the percentage of predicted discharge varies significantly based on different model outputs.

Different models with a high range of results are observed from different global climate change models. Mirza (2002) found, based on model results, that the probability of increase of flood discharge because of temperature rise is less in the Brahmaputra than that of the Ganges and Meghna Rivers. Later, developing an empirical model, Mirza (2005) found that 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°C. 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. Afterwards, IWM (2008) studied the impacts of climate change on monsoon flooding in Bangladesh. It considered the A1F1 emissions scenario, assuming a 13% increase in precipitation over the Ganges, Brahmaputra, and Meghna Basins, and found a corresponding 22% increase in the peak discharge at Hardinge Bridge of the Ganges River.

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°C, 1.55°C, and 2.4°C with a median precipitation increase of 1%, 4%, and 6%, respectively. Accordingly, the monsoon discharge would increase by 2050 (Figure 11), but the monthly increase rates would be different by 2050 based on five generator condition monitor and two special report on emissions scenarios model experiments (Yu *et al.*, 2010). Likewise, the rates would also 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, respectively.

Increased rainfall and increased SLR, associated with the effect of climate change, are the two factors that would induce the flooding in 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. Both of these climate change–induced factors would ultimately result in an increase of flooded area and inundation depth. The digital elevation data of Bangladesh indicates that more than 50% of the area is less than 5 m above mean sea level. Therefore, a 1-cm SLR would have socioeconomic consequences for the country.

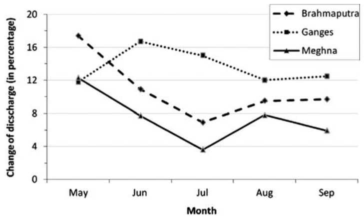

Figure 11. Estimated average changes of percentage in discharge.

Different studies on inundation have found varying results. A 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% total land inundation because of a SLR of 1 m. Nevertheless, about 11% (4,107 km^2) 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 km^2) 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 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 for flooding. Brammer (2004) indicated the flood-vulnerable areas qualitatively based on agroecological regions. He also indicated that after the next 50 years, it is likely that flooding will increase in the Middle Meghna floodplain, middle section of the Low Ganges River floodplain, Old Meghna estuarine floodplain, and low-lying Sylhet Basin because of impeded drainage.

As sea level continues to rise, the associated effects of permanent inundation are likely to increase salinity near coastal areas. WARPO (2005) showed that a 5-ppt saline front would penetrate about 40 km inland for a SLR of 88 cm, which would affect the only freshwater pocket of the Tentulia River in the Meghna estuary. A big chunk of the freshwater zone would disappear because of SLR near the estuary. Salinity intrusion would have a comprehensive effect on the country's ecology and lead some of its endangered species into extinction.

Moreover, increased salinity intrusion because of SLR would pose a great threat to the Sundarbans. The Sundarbans have already been affected by reduced freshwater flow from the Ganges River through the Gorai River after construction of the Farakka Barrage in 1970s upstream to divert water to the Calcutta Port in India. Presently, no flow is coming through the Gorai River, particularly during the dry season. So, salinity front is already landwards. Further SLR would lead to a definite inward intrusion of the salinity front, causing different species of plants and animals to be adversely affected. Increased saltwater intrusion is considered one of the causes of top-dying of Sundari trees. A SLR of 32 cm would cause intrusion of 10 to 20 ppt more salinity into the Sundarbans. The rate of saltwater intrusion would also affect the ability of the ecosystem to adapt. IWM and CEGIS (2007) has predicted that the present brackish water area (about 21,520 km^2) would increase to 24,410 and 25,790 km^2 at 27- and 62-cm SLR, respectively.

CEGIS (2010) also carried out research to assess the impact of climate on the morphological process of the main rivers and the Meghna estuary. They identified that with the changes in sea level, the rivers would adjust their bed and bank levels with a certain time lag, which mainly depends on their proximity to the sea. The tidal plains in the Meghna estuary would respond quickly because of its propinquity to the sea, if it were not empoldered. Moreover, impacts of climate change are presently assessed considering a fixed river system, while the river system is continuously adjusting with the changing of different parameters, such as base level, flood discharge, and sediment input from upstream. The estuary, tidal plains, and floodplains, along with the river system, would adjust themselves with the increased flood discharge and subsequent SLR. Thus, whatever the impacts of climate changes have been assessed so far, they might differ to different extents if the system is considered while taking into account dynamically adjusting processes with the changed situation. This dynamic approach needs to be considered for representing the dynamic delta.

Role of Assam Earthquake 1950

Drastic changes in the G-B Basins were observed in the past as a result of major seismic activities (Gupta *et al.*, 2014). Seismic events in the Brahmaputra Basin (Goodbred *et al.*, 2003) would also change the sediment scenario and its responses. The 1950 Assam earthquake, with a magnitude of 8.5 on the 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 a sediment wave and took nearly five decades to complete its journey to the bay (Sarker, 2009; Sarker and Thorne, 2006). Sarker, Akter, and Rahman (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 would affect the water level in the Shahbajpur Channel and in the Lower Meghna River. Analysis of monsoon water levels at 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 or changes to the local morphology of downstream channels. Unfortunately, there are 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.

CONCLUSIONS

Avulsion of the Brahmaputra and Teesta, gradual shifting of the Ganges, tectonic subsidence and uplifting, deltaic subsidence, and delta progradation are the main drivers that influence the hydromorphological development of the river systems of Bangladesh. In addition, human interventions, such as construction of dams, barrages, coastal polders, and flood embankments; unplanned land-use changes; and groundwater abstraction, have triggered the changing processes. However, the active functioning of those drivers varies greatly depending on the regional physical characteristics, such as the Madhupur and Barind Tracts. Moreover, seismic events, such as the 1950 Assam earthquake, have pronounced effects on the delta building process. Huge piles of sediment generated by the earthquake have expedited the delta building process through delta progradation, which is also responsible for floodplain and tidal plain development through the river morphology adjustment process. An alteration of one driver causes a series of alterations. In general, avulsion of the Brahmaputra River, tectonic activities, deltaic subsidence, and human intervention, along with delta progradation, are the main drivers that have influenced the overall river characteristics of Bangladesh on different scales.

Studies on a tide-dominated delta, such as the Bengal Delta, and predictions for coming decades are sparse. Although a few studies have identified the dominant drivers in changing the morphology of the delta during the last 250 years, they identified qualitative roles of the delta development process in adjusting the rivers, floodplain, and coastal plain. The key process mostly depends on sediment availability and proportion, which may change in the future because of upstream intervention, agriculture practices, and land management. Any flow and sediment change in the catchment would affect the delta morphology. Other important drivers are annual input of water and sediment, composition of sediment, seasonal variability of the flow, human interventions, and SLR, although a major part of the catchment of the rivers, about 93%, is outside of Bangladesh and the country has barely any control over it. Climate change, as well as human intervention, may alter both flow and sediment regimes and finally delta morphology.

Therefore, it is necessary to understand the response of the delta morphology as a response to changes in the flow regimes, both in the dry season and the monsoon; changes in sediment, both fine and coarse, because of climate change and human interventions outside Bangladesh; changes in RSLR; and interventions in the delta area. However, other research gaps in the delta area need to be addressed before development planning in the delta is undertaken.

Although several studies have addressed the Holocene development of the Bengal Delta, no significant studies (only a few microscale studies) have addressed the decade- to century-scale development of the whole delta. The unavailability and unreliability of sediment data restrict scientists in working on this issue. However, the latest numerical models may help to hindcast the delta data in preparation for decade- to century-scale forecasting.

Information on the vertical adjustment processes of the tidal plain with rising of RSLR or tidal level is not available. This is an important issue in developing strategies for long-term planning to adapt with climate change–induced SLR. The impact of polderisation also must be addressed, and some modelling exercises have already been done. Although some indicative research on the morphological timescale of the rivers, estuaries, and tidal plains in adjusting to SLR and increased flood discharge have been done, more research is needed depending on the availability of sediment in the context of climate change and human interventions for long-term planning of these timescales.

Deltaic subsidence is relevant for long-term planning, although recent studies indicated very high uncertainty ranges from 1 to 25 mm/y. Further research on subsidence may provide a rational rate of subsidence to plan and design with purpose of addressing climate change–induced SLR. Because a huge cost is involved with every unit design in terms of height of the coastal structural defence, further research is needed on the subsidence rate.

Coastal polder has altered the natural land sedimentation process. If there is no sedimentation, then land erosion will prevail. Thus, the rate of subsidence is necessary. The rate of floodplain sedimentation with the changes of SLR or tidal range and availability of sediment has not been studied yet. Information on these matters may help in formulating an adaptation strategy for climate change and subsidence.

The main rivers of Bangladesh have been transporting about 1 billion tonnes of sediment every year, out of which one-fourth is fine sand. The rest of the sediment consists of silt and clay. The roles of fine and coarse sediments in the land accretion process would be different. Knowledge of the roles of these fine (silt and clay) and coarse (fine sand) sediments on the lateral and vertical accretion processes requires further elaborations for this delta plain.

Finally, a process response model needs to be developed on the delta development processes, which may help to predict the response of the delta in the changed conditions for long-term planning. Prevailing processes that have already been identified could be incorporated in that process response model to test future unequivocal scenarios.

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