Sediment dispersal processes and management in coping with climate change in the Meghna Estuary, Bangladesh

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Abstract Due to flat terrain and dense population, the Bengal Delta is highly vulnerable to sea level rise. At present the delta building process is active in the Meghna Estuary. Information on sediment dispersal processes in the estuary and their response to different exogenic and anthropogenic forces is an important requirement for managing the sediment and developing adaptive measures to counter the potential impact of climate change. Historical maps, satellite images and tidal water level data were analysed and the response of the Meghna Estuary to extreme events, e.g. the 1950 Assam earthquake, as well as anthropogenic interventions, was assessed. The issue of sediment management was addressed, based on an understanding of the response of the estuary to the extreme natural event and anthropogenic interventions, along with an assessment of the response of the estuary to sea level rise. Among other interventions, emphasis has been directed to promoting vertical accretion by injecting sediment into polders.

Key words Bengal delta; Meghna Estuary; sea level rise; sediment dispersal processes; vertical accretion; sediment injection

INTRODUCTION

Deltas are a large accumulation of both fluvial and marine sediments which have infilled river mouths and extended onto the continental shelf (Fookes *et al*., 2007). Deltas are generally associated with large catchments with high sediment yields and low nearshore gradients. In the last few decades most deltas in the world have been experiencing shoreline retreat and land loss due to the impacts of human activities such as damming, channelisation, and water and soil conservation within the upstream river basin (Fan *et al*., 2006). The Mississippi and Nile deltas are losing land at a very high rate (Gagliano *et al*., 1981; Frihy *et al*., 1998), while the Yellow River delta is in a destructive phase. The Bengal delta is the world's second largest delta comprising 100 000 km^2 of riverine flood plain and deltaic plain (Goodbred *et al*., 2003; Hori & Saito, 2007). The great rivers, the Brahmaputra and the Ganges with their huge sediment loads derived from the Himalayas, and tectonic interactions have formed this delta. A large part of this delta lies within Bangladesh, an independent country that extends from 20°34′ to 26°33′ latitude and between 88°01′ and 92°41′ longitude (Rashid, 1991), covering a land area of 144 000 km^2. Most of the country is formed by a low lying plain with a gentle slope from north to south, where the land meets the Bay of Bengal (Elahi, 1991).

At the time of the last census in 2001, the population was just over 124 million, with a growth rate of about 1.58% per annum (Bangladesh Bureau of Statistics, 2006). The average population density is 843 people per km^2, which makes Bangladesh one of the world's most crowded countries. Moreover, Bangladesh is poor, as the *per capita* income is only US$445 (Economic Advisor's Wing, 2005). All of these factors force the people to live in places that are highly vulnerable to flooding, erosion and inundation. Compared to the human impact in the Mississippi or the Yellow River basins, the Brahmaputra and Ganges basins are less modified. However, future drivers, such as intense human impact and sea level rise, may make the entire system more vulnerable to inundation and erosion.

At present, delta building is taking place within the Meghna Estuary area (Fig. 1). Each year the Ganges, Jamuna (lower reach of the Brahmaputra) and Meghna rivers of Bangladesh transport more than one billion tonnes of sediment from their catchments in India, China, Nepal and Bhutan to the delta region. According to the long-term sediment budget for the delta predicted by Goodbred & Kuehl (2000), one third of the sediment carried by these rivers is deposited on the flood plain and tidal plain, and one third is trapped in the sub-aqueous delta, causing vertical accretion and lateral progression of the sub-aqueous delta. Goodbred & Kuehl (2000) were unable to assess the destination of the remaining sediment and concluded that it was probably transported to the deep ocean floor.

Due to high sediment input from upstream and high tidal energy, the estuary itself is very dynamic in nature and characterized by erosion and accretion on the scale of several thousand hectares of land per year. Although accretion is the dominant process, several thousands of people in the densely populated tidal plains become landless and homeless every year due to erosion.

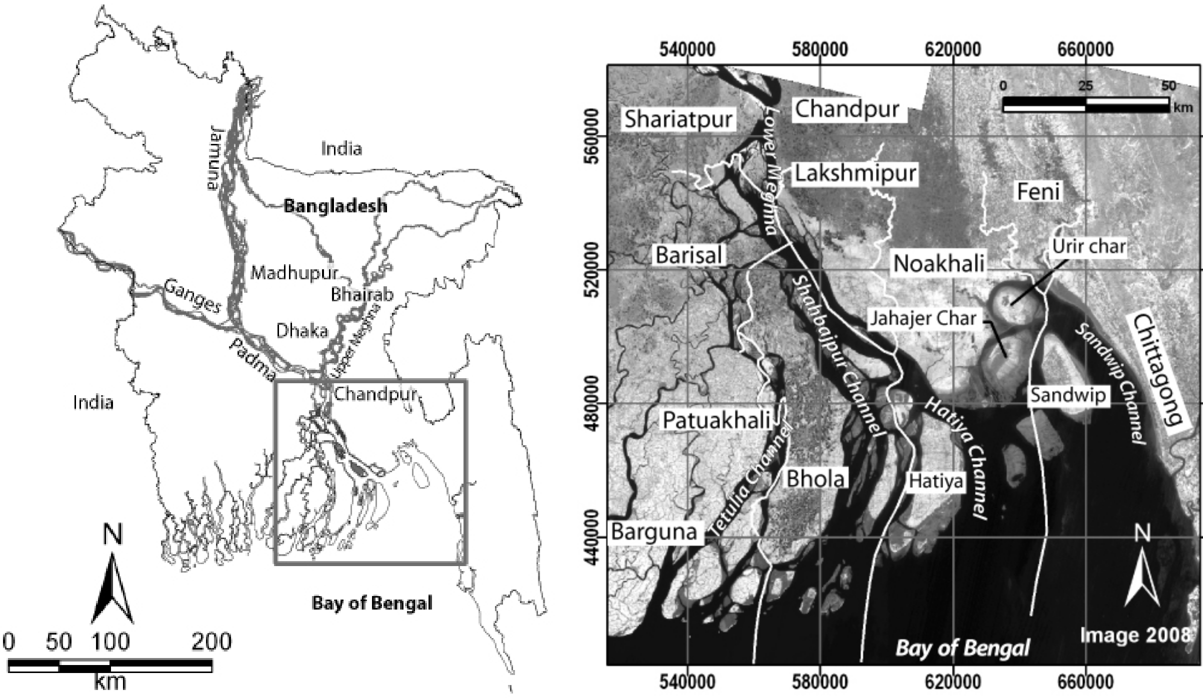

Fig. 1 Satellite image of 2010 shows the Meghna Estuary area, in Bangladesh.

Both endogenic factors, such as the shifting of river mouths as a consequence of the delta building processes, and exogenic factors, such as changes of base level, due to climate change, have long-term (1000-year timescale) effects on the development of the estuary. However, changes due to sediment input, which is sensitive to human activity and natural hazards, such as frequently occurring earthquakes (Goodbred *et al*., 2003), may have impacts on the decadal scale. The large sediment input resulting from the 1950 Assam earthquake is believed to have significantly influenced the topography of the estuary (Brammer, 2004). Also, human activities, such as the construction of flood embankment and polders in the tidal plains, have restricted the flood plain and tidal plain sedimentation and pushed more sediment into the bay. Assessing the effects of the large events that have occurred in recent decades would be helpful for assessing the future development of the delta.

Due to its low and flat terrain, it is suspected that Bangladesh would be one of the worst victims of climate change (Ahmed, 2006). Sediment management, based on a sound knowledge of the processes of sediment dispersal in the estuary and of the effects of large events in the recent past, could be instrumental in combating sea level rise. Up-to-date knowledge and identification of related issues may help in formulating the most effective adaptive approach.

Since the late 1970s, three studies have been carried out with financial support from the Netherlands government, namely the Land Reclamation Project (LRP), the Meghna Estuary Studies (MES) and the Estuary Development Programme (EDP) of the Bangladesh Water

Development Board (BWDB). These studies greatly increased knowledge and understanding of the physical processes operating in the estuary. This contribution draws heavily on the data and information generated by these studies. Historical maps and time-series satellite images and tidal water level data have been analysed to understand the land formation and sediment dispersion processes and to assess the impact of exogenic factors and human intervention.

PHYSICAL SETTING OF THE MEGHNA ESTUARY

The area covered by the EDP of the BWDB is the area of the Meghna Estuary, the northern limit of which is Chandpur and with the southern boundary stretching more than 200 km from east to west (Fig. 1).

Every year, the Ganges, the Brahmaputra and the Meghna discharge about 1×10^{12} m^3 of water into the Lower Meghna River. The flow carried by the Lower Meghna River is distributed by a number of channels to the estuary. Currently, the Tetualia Channel carries about 15% of the monsoon flow, and the Hatiya Channel about 10%, and the rest is carried by the Shahbajpur Channel (MES II, 2001). It should be mentioned here that the distribution of river and tidal flow in the estuary has not been fixed over the years. Due to the very dynamic characteristics of the estuary, the sediment laden river flow distribution processes change very rapidly. Several large islands have existed in the estuary for centuries, e.g. Bhola, Hatiya and Sandwip. The sizes, shapes and locations of these islands have been changing over time, but these islands play a key role in distributing the flow and sediment in the estuary.

The beds of the channels in the estuary consist of fine sand and silt (25–50%), the representative grain size of which varies from 0.016 to 0.25 mm. However, in the suspended sediment the fraction of fine sand is very negligible, indicating that sand particles move as bed load (MES II, 2001). Analysis of bulk suspended sediment samples collected from different depths also showed hardly any variation. The concentration of suspended sediment was found to be very high and the maximum concentration was 9000 ppm.

Tides are semidiurnal in the Bay of Bengal. The tidal range varies from 0.6 to 1.4 times the average range during neap and spring tides respectively (Sokolewicz & Louters, 2007). According to Hayes (1979), estuaries can be divided into three categories on the basis of tidal range, i.e. micro-tidal (0–2 m), meso-tidal (2–4 m) and macro-tidal (>4 m). All three of these characteristics are present in the Meghna Estuary. The micro-tidal range is present in Tetulia Channel and the Lower Mehgna River close to Chandpur and the meso-tidal range is observed at the south of Bhola Island and north of Hatiya Island (Fig. 1). In the east of the Hatiya and Sandwip channels, the tidal range falls in the macro-tidal category. The maximum tidal range (>) 8.6 m was observed in the northeast corner of the estuary.

Sediment load observations were made in the Jamuna, Ganges and Padma rivers in the early 1990s, including information on the magnitude of the fine (silty clay) and coarse (fine sand) components of the total load (Table 1). The combined sediment load of the Jamuna and Ganges rivers, inputs and outputs through the tributaries and distributaries, flood plain sedimentation and changes in the storage of the riverbed control the sediment load of the Padma River – the direct fluvial input to the Meghna estuary. Out of 950 million tonnes of sediment, >75% is silt and clay and the rest is composed of fine sand.

Table 1 Mean annual suspended sediment loads, based on sediment measurement of FAP 24 from 1994 to 1996 (CEGIS, 2010).

Period	Type of sediment	Jamuna	Ganges	Padma
1994–1996	$S_{wash\ load}$ (Mt year^{-1}	280	560	720
	$S_{suspended\ bed\ load}$ (Mt year^{-1})	125	75	230
	S_{total} (Mt year^{-1})	405	635	950

The Meghna Estuary is a well mixed system; no stratification was observed during any measurement campaign in the 1990s (MES II, 2001). Salinity in the estuary varies over a very wide range from the monsoon to the dry season. Very high discharges in the Lower Meghna River pushes the salinity far into the bay. During the dry season fresh water flow in the river reduces about 20-fold, resulting in salinity intrusion into the estuary. Salinity up to one p.p.t. (parts per thousand) may intrude up to the northern end of the Shahbajpur Channel. In the eastern part of the estuary the salinity may reach up to 10–20 p.p.t. Salinity in the Meghna Estuary area never reaches the salinity level of sea water (~34.5 p.p.t.) (Sokolewicz & Louters, 2007).

THE HISTORICAL DEVELOPMENT OF THE MEGHNA ESTUARY

The survey of Rennels in the 1760–1770s showed that the Padma and the Meghna entered the estuary at two different locations on the northwest and northeast sides of the then Bhola Island, respectively (Fig. 2). The Padma followed a course close to the present day course of the Tetulia Channel and the Meghna flowed eastwards along the northeast side of Bhola Island. At that time the Brahmaputra flowed on the eastern side of the Madhupur Tracts and joined the Meghna somewhere close to Bhairab, about 80 km north of Chandpur.

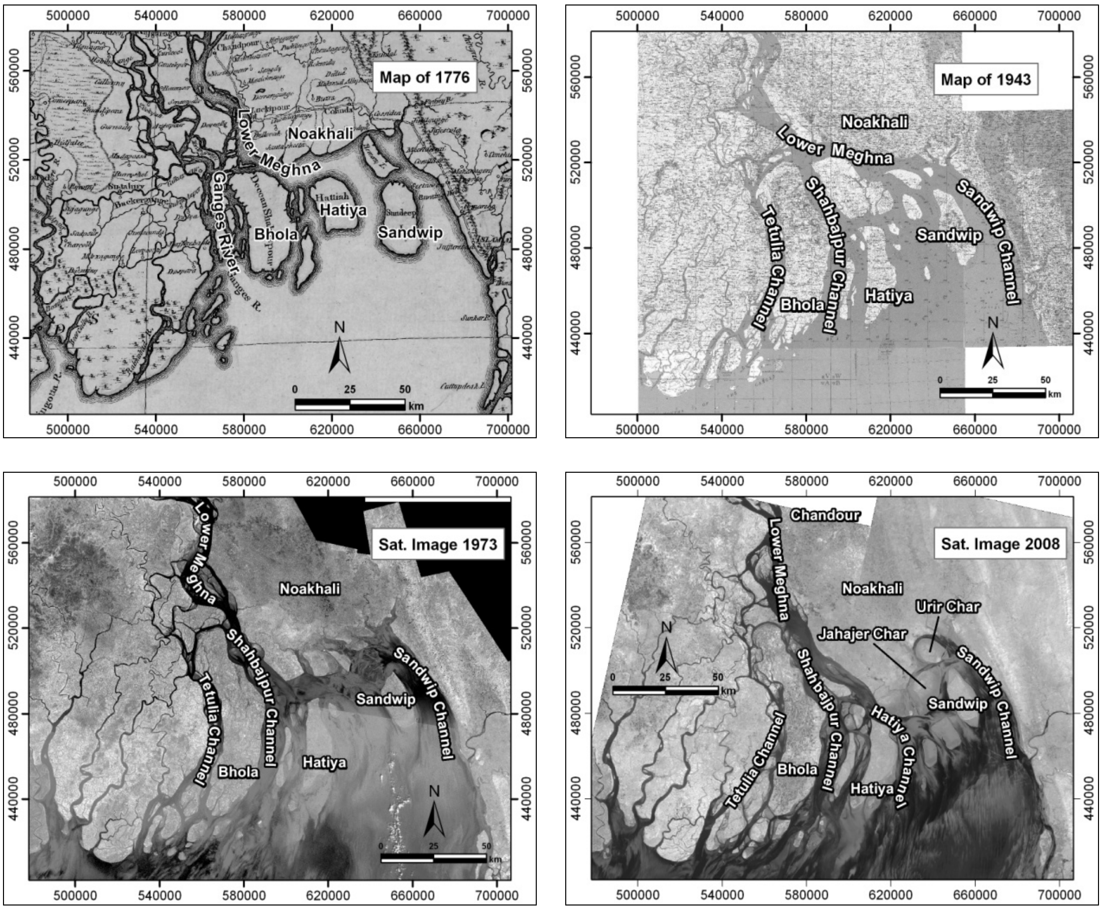

Fig. 2 Meghna Estuary in 1776, 1943, 1973 and 2008.

By the early 19th century, the flow of the Brahmaputra joined with the Ganges at Aricha and flowed in a southeast direction as the Padma up to Chandpur where it met with the Meghna River. In 1943, the combined flow of the three great rivers divided into three channels at the northeastern tip of Bhola Island–the Meghna, Shahbajpur and Tetulia channels. The Meghna River flowed along an eastward course from the upstream tip of Bhola Island. At that time, Noakhali town was on the left bank of the Meghna River and further downstream the flow was tri-sected by small islands. The shoreline at Noakhali retreated to the north by several km over the period of 170 years from 1776 to 1943, but the magnitude of shoreline changes was not that significant, considering the long period of time. However, the shapes, sizes and locations of the islands of Bhola and Hatiya changed a lot. Land accretion during this period was mainly limited to the southwestern part of the Meghna Estuary. However, the changes from 1943 to 1973 are very striking. The course of the Meghna River, in the east of Bhola Island, was abandoned, resulting in the shifting of flow to the Shahbajpur Channel. The Hatiya Channel was separated from this channel at the north of Hatiya Island. A very large land mass accreted to the south of Noakhali and Bhola. The change in 30 years from 1943 to 1973 was enormous and the extent of land accretion was also very high. During the following decades the development of the Meghna Estuary followed a similar trend, but the rate of change slowed down significantly.

SEDIMENT CIRCULATION PROCESSES IN THE ESTUARY

Sediment supply, waves and tides exert important controls on the formation of the delta planform – a birdfoot delta, such as the Mississippi delta, represents a river-dominated delta where the prevailing waves and tides have low energy. In contrast to the Mississippi, high tide energy results in tide-dominated deltas like the Meghna Estuary, where distributary channels with linear river mouth bars are present (Fookes *et al*., 2007). Sediment deposition occurs only by river flushing in the river dominated delta, while in tide dominated deltas, sediments are reworked and redeposited (Hori & Saito, 2007). Every year about 1×10^{12} m^3 of fresh water is brought into the Meghna Estuary by the three major rivers: the Ganges, the Jamuna and the Upper Meghna. This water is distributed into the estuary by three distributary channels, namely the Tetulia, Shahbajpur, Hatia and Hatiya channels. However, the ratio of the distribution of fresh water varies with the season and also over a period of decades, depending on the channel developing processes in the Meghna Estuary.

The sediment distribution process in the estuary is mainly governed by the sediment characteristics, the tidal range and its characteristics, waves and the estuary planform (Palinkas *et al*., 2006; Bird, 2008). Seasonal variation of the fresh water input into the estuary ranges from 20 to 30 times, a similar range to that of sediment input. Most of the river-borne sediment enters the estuary during the few months of the monsoon. A major part of the sediment, especially the finer fraction, takes temporary residence in the zone of the turbidity maximum, which is close to the lower limit of the Shahbajpur Channel (Sokolewicz & Louters, 2007). Sediment concentrations at those locations are very high at about 2000 ppm (MES II, 2001). The turbidity maximum generally occurs in the low salinity zone and shifts its location with the changes in flood discharge (Grabemann *et al*., 1995). Before reaching its final destination, fine sediment moves with the changes of the turbidity maximum and also back and forth with the tide. During the dry season the sediment supply from the catchment becomes insignificant, but sediment concentrations in the northeastern tide dominated part remain close to that of the monsoon (IWM, 2009, 2010). The temporary storage of sediment during the monsoon in the zone of the turbidity maximum is the main source of sediment redistribution during the dry season.

The relative strength of flood and ebb tide determines the locations for sedimentation build up (Bird, 2008). Generally, higher flow velocity during flood tide in the shallow estuary brings sediment to the landward inter-tidal areas to settle. This is known as the so-called tidal pumping process. A tidal circulation process disperses fresh water and river-borne sediment into the northeastern part of the estuary. Tidal residual flow in the Meghna Estuary, as obtained from a mathematical model and field observations, showed that a part of fresh water that enters through the Shahbajpur and Hatiya channels makes nearly a u-turn and forms loop-type circulations around Sandwip, Urir Char and Jahajer Char (Fig. 3). Based on the MES II (2001) and Sokolewicz & Louters (2007), the relative importance of river and tidal flow with respect to sediment discharge has been drawn on satellite images of 2010 (Fig. 3). It shows the tidal meeting points and subsequent sedimentation in the northeastern part of the estuary. It can be seen in the following sections that a very high sedimentation rate is associated with this type of tidal circulation process.

The maximum flow velocity of 4 m s^{-1} was also observed in the northeastern part of the estuary in the Sandwip Channel (MES II, 2001) with a maximum sediment concentration of about 9000 ppm. Recent measurement shows that the values of maximum flow velocity and sediment concentration are very similar in the monsoon and the dry seasons (IWM, 2009), although the riverine sediment input during the dry season is negligible during this period. The monsoon sediment was moved temporarily by the river flow and was forced to remain close to the southern boundary of the estuary (downstream of the Shahbajpur Channel), having been brought to the northeastern side by tidal circulation and tidal pumping processes. The fine fractions of the sediment dominate the sediment redistribution process (Sokolewicz & Louters, 2007).

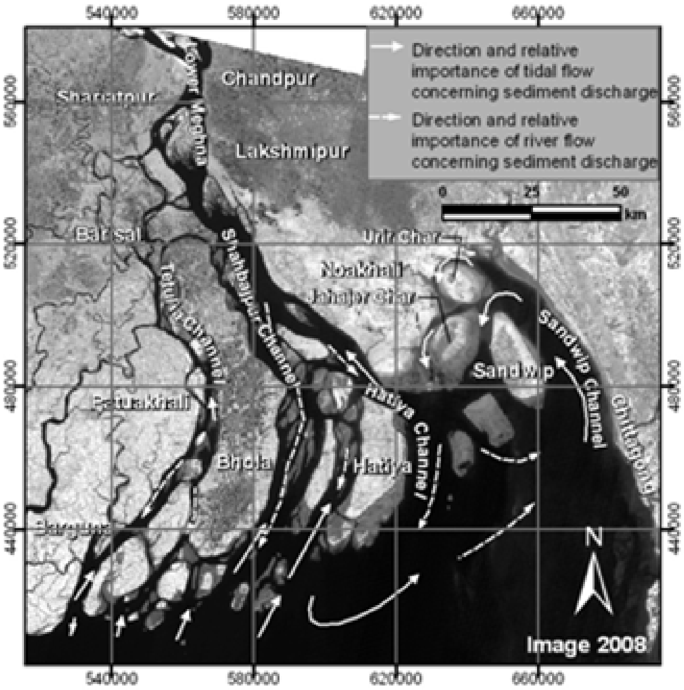

Fig. 3 The direction and relative importance of river and tidal flows in influencing sediment discharge (based on Sokolewicz, & Louters, 2007).

THE PROCESS OF LAND FORMATION

In the estuary, the process of land formation is visible when a bar (composed of fine sand, silt and clay) emerges during low tide. Time-series satellite images show the land formation process in different parts of the estuary. Initially the elevation of the bar is very close to, but higher than, the average low tide level. Over time, the elevation increases and the coverage of the bar surfaces changes (Fig. 4). It is first colonised by Uri-grass (*Portaresia coarctata*). In most cases, the Bangladesh Forest Department transplants mangroves at a certain stage of development of the bar. After rising to a certain level very close to the average high tide (depending on the prevailing tidal range), mangrove forests dominate the land surface and people start to settle there. As the tidal variation differs through the estuary, the time required for land development from its initial emergence to its inhabitation also varies.

The time required for the development of land from its first emergence above low tide level to full cover by mangrove forests or initiation of settlement, varies from place to place. The fastest land development as observed within the Shahbajpur Channel from time-series satellite imagery is

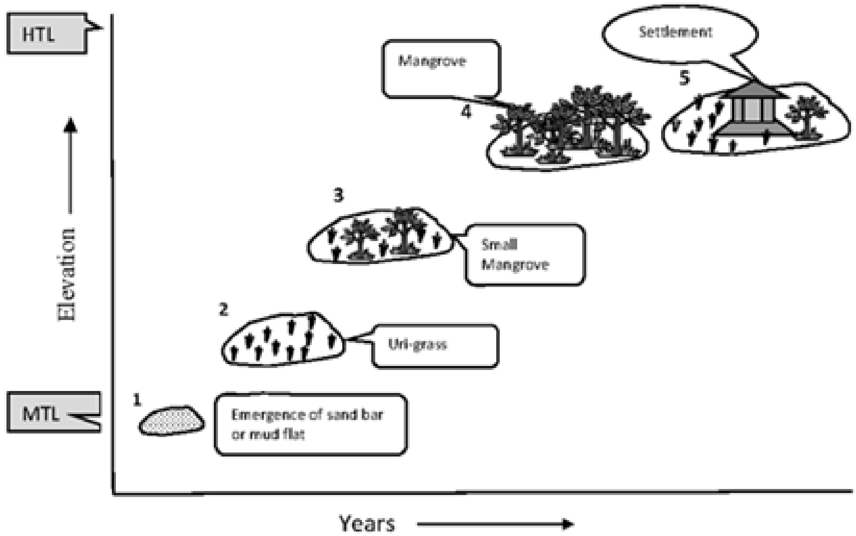

Fig. 4 The process of land formation in the Meghna Estuary.

Table 2 The time required for land development at different locations in the Meghna Estuary.

Locations	Dominant process	Mean tidal range (m)	Time required for land development (year)
Outfall of Tetulia Channel	Marine	2	22
Shahbajpur Channel	Mixed energy	2	12
South of Noakhali	Mixed energy	3	12
Urir Char	Marine	6	16

8 years. In some parts of the Tetulia Channel, it was found to be as much as 25 years. The average time required for land development at different locations is shown in Table 2, with the mean tidal range of the location concerned. It is found that the time required for land development is not dependent on the tidal range, although higher tidal range demands higher amount of sediment for the same magnitude of land development. The land development process is relatively rapid where both riverine and marine processes are active. However, sediment availability might be another factor. The Tetulia Channel at its outfall is dominated by a marine-dominated process and the time required for land development is the highest compared to other locations. But the situation is different in Urir Char where marine dominated processes also prevail. Very active tidal circulation and sediment pumping processes ensure the availability of sediment for land formation in the south of the Noakhali and Urir Char area.

LAND FORMATION

Erosion and accretion in the Meghna Estuary have been studied in the past by several agencies and researchers, including Eysink (1983), EGIS (1997), Allison (1998) and MES II (2001). The study periods varied from a few years to several centuries. The longer-term estimates were based on historical maps, such as the Rennels Map (1776), the Commander Lloyd' chart (1840), historical maps (1940), and satellite images for different years after 1973. The results of all these studies show that accretion has been the dominant process during the last 200 years in the coastal areas of Bangladesh (Table 3).

Based on the analysis of satellite images, MES II estimated erosion and accretion for the period 1973–2000 (Table 4). During this period 86 400 ha were eroded while 137 200 ha were accreted, resulting in a net accretion of 50 800 ha, which is equivalent to the net accretion rate of

Table 3 Comparison of erosion and accretion rates from different studies (MES II, 2001).

Length of study period (years)	Period of study	Net change for period (km^{2})	Rate of change (km^2 year^{-1})	Reference
220	1776–1996	+2187	9.9	EGIS (1997)
192	1792–1984	+1346	7.0	Allison (1998)
144	1840–1984	+638	4.4	Allison (1998)
23	1940–1963	+279	12.1	Eysink (1983)

Table 4 Erosion and accretion from 1973 to 2000 (MES II, 2001).

Period	Change (km^2)		Rate of change (km^2 year^{-1})		Net accretion (km^2)	Rate of net accretion (km^2 year^{-1})
	Erosion	Accretion	Erosion	Accretion		
1973–2000	860	1370	32	21	510	18.9

18.9 km^2 year^{-1}. The total accretion was about 60% higher than the erosion over a period of 27 years and about 2.7 times higher than the net accretion. The very high annual rates of erosion (32 km^2 year^{-1}) and accretion (51 km^2 year^{-1}) emphasize the highly dynamic character of the Meghna Estuary.

Analysis of satellite images of 1973 and 2008 shows that the net rate of accretion of newly developed land is very high in the Noakhali district, followed by Patuakhlai and Chittagong. Residual tidal flow (Fig. 3) also indicates that the Noakhali district is the most sediment-deposition prone area in the Meghna Estuary. In other districts land erosion is almost balanced by accretion. Analysis of erosion/accretion for smaller time-steps suggests that the net accretion at Patuakhali occurred in a particular period. On the other hand, net accretion dominated in Noakhali district during 1973–2008, as shown in Fig. 5. These findings suggest that the tidal circulation process was the main contributor to the net land formation.

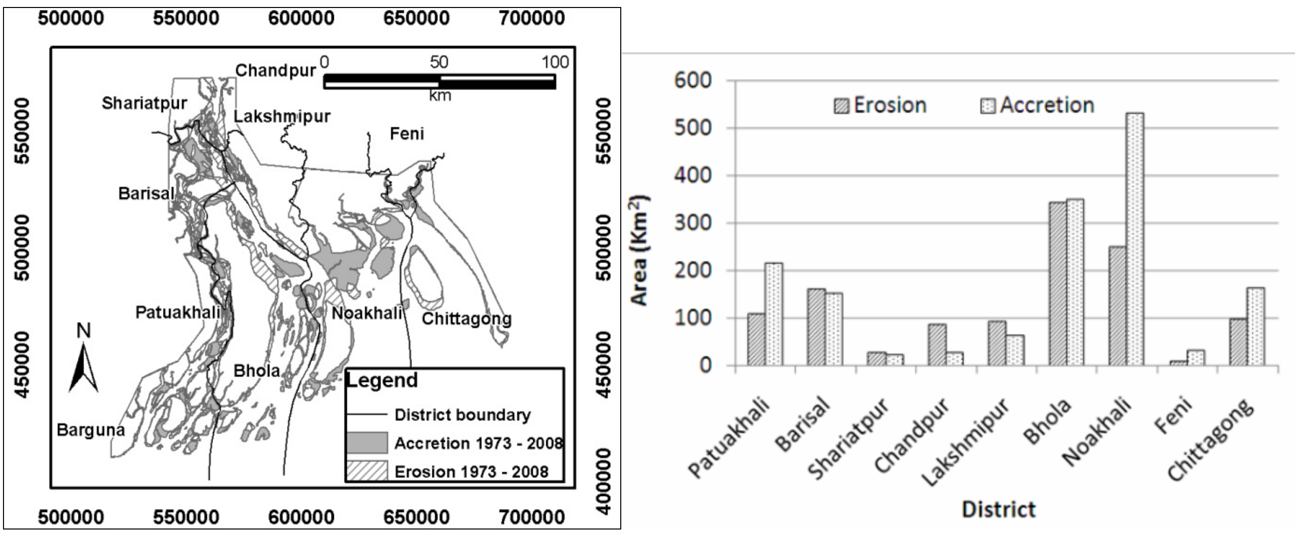

Fig. 5 Erosion and accretion in the Meghna Estuary during the period 1973–2008.

ASSESSING THE IMPACTS OF EXOGENIC FACTORS AND HUMAN ACTIVITY

During the last six decades the catchments of the Ganges and Brahmaputra rivers have been impacted by a major natural events and large-scale human activity. Both of these are likely to have had significant effects on the morphological changes in the Meghna Estuary. An earthquake in

1950 in Assam, India caused landslides in the Himalayas, which displaced approximately 45×10^9 m^3 of earth (Verghese, 1999). Much of this material entered the Brahmaputra River from Assam. The finer fraction (silt and clay) of the sediment was transported downstream very rapidly as wash load without changing the morphology of the river, and most of this sediment was deposited in the Meghna Estuary (Verghese, 1999; Sarker & Thorne, 2006). The coarser fraction of the sediment propagated a sediment wave that moved through the system and entered the Meghna Estuary in the mid-1970s. The crest of the sediment wave passed through the Lower Meghna and Shahabzpur Channel in the 1980s (Sarker & Thorne, 2006; Sarker, 2009). Moreover, there were other major disturbances in the catchments of these rivers, including intensive agricultural practices and deforestation (Verghese, 1999; Hofer & Messerli; 2006), construction of flood embankments along the river levees and construction of coastal embankments in the 1960s and 1970s. Many researchers (Hofer, 1998; Mirza *et al*., 2001; Mirza, 2002) have, however, been unable to find any evidence that could suggest an increase in flood magnitude or sediment concentration in recent years due to deforestation in the Himalayas or extensive changes in land use in the catchments of other rivers.

To assess the impact of exogenic factors and human activity during the period extending from 1776 (when relatively reliable historical maps became available) to 2008, the period was divided into three periods, namely, 1776–1943, 1943–1973, and 1973–2008. The latter 35-year period was subsequently also divided into smaller periods to assess the effects of the sediment wave that entered the estuary. The three major periods were defined on the basis of: (i) the rate of net accretion before the 1950 earthquake and prior to any major intervention in the flood plain and tidal plains, (ii) the rate of net accretion as an effect of the 1950 earthquake, and (iii) the rate of net accretion after the construction of flood embankments and polders.

The historical maps and geo-referenced satellite images were co-registered to minimise the errors. Error may be generated during the delineation of the shoreline from satellite images. The shoreline coincides with the physical interface of land and water (Dolan *et al*., 1980). Although its definition is simple, in practice it is a challenge to apply it. The position of the shoreline changes continuously due to cross-shore and along-shore sediment transport and especially due to the continuous variation of water level with the tide at the coastal boundary (Boak & Turner, 2006). To nullify the effect of tidal variation, a method of delineating the shoreline from satellite images was developed by CEGIS (2009). Errors in the delineation of the shorelines were also introduced by the pixel size of the images and the presence of a wide intertidal flat. However, because the changes were very large compared to the error margins, the final output does not involve significant errors.

The rate of net accretion was very low during the 167 years extending from 1776 to 1943. The net increase in land area was 760 km^2, which is equivalent to a mean annual accretion rate of 4.6 km^2 $year^{-1}$. Based on Umitsu's (1993) paleo-geographic maps of the delta, Allison (1998) estimated that since the delta started to prograde from 6500 to 7000 BP, its net rate of accretion is 4–5 km^2 $year^{-1}$. This value is very close to the net accretion rate estimated for the period 1776–1943. In the following 30 years (from 1943 to 1973), the net accretion became very high, with the land area increasing by 1100 km^2. This is equivalent to a mean annual net accretion rate of 36 km^2 $year^{-1}$. During the last 35 years, the net accretion rate has reduced to 17 km^2 $year^{-1}$ (Fig. 3). This rate is slightly less than the net rate of accretion estimated by MES II in 2001 for the period 1973–2000 (Table 4). These results indicate that during the last 65 years (from 1943 to 2008), about 1700 km^2 of land has been formed within the Meghna Estuary.

There are clearly problems in making a direct comparison of the net rate of accretion estimated from maps providing a temporal resolution of about 200 years with that estimated from other maps and images providing a temporal resolution of three decades. However, the difference is very large, suggesting that the rate of net accretion was very low until 1943 and that there was a sudden increase in net accretion during the subsequent three decades, followed by a substantial decrease. The rate of accretion immediately after the earthquake was much higher than the rates estimated by several different studies (Table 3).

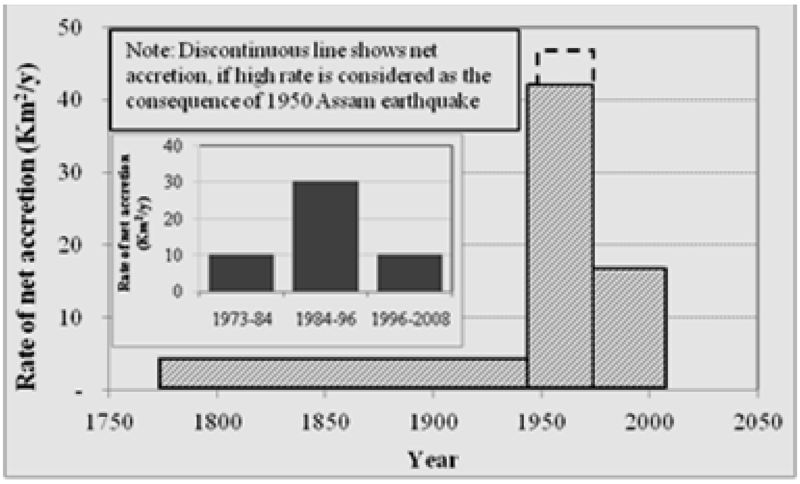

Fig. 6 Net accretion in the Meghna Estuary during the last 232 years.

The sudden increase in net accretion has been explained by Sarker & Thorne (2006) and Sarker (2009). They hypothesised that the Assam earthquake in 1950 produced a huge amount of sediment which entered the Brahmaputra River. The finer fraction (silt and clay) of the sediment subsequently travelled through the system without modifying the river morphology. After mixing with the saline water in the estuary, a major part of this sediment was deposited, resulting in a significant amount of land accretion in the south of the Noakhali and Bhola districts. If the existing long-term accretion rate is considered to have continued during the period extending from 1943 to 1950, the rate of land accretion after the earthquake can be assumed to have been even higher and to have reached more than 46 km^2 $year^{-1}$ (Fig. 6). Construction of two cross-dams in the late 1950s and early 1960s in Noakhali might also have influenced the process of accretion. However, the huge amount of sediment required to account for this accelerated accretion was the sediment supplied by the landslides generated by the earthquake.

If the period from 1973 to 2008 is split into three nearly-equal time-spans, based on the availability of satellite images in the CEGIS archives, the net accretion shows distinct variations over time. After 1973, the rate of accretion in the next 11 years was found to have decreased to 10 km^2 $year^{-1}$. However, in the following 12 years, extending from 1984 to 1996, the net accretion rate increased to 30 km^2 $year^{-1}$. This period of high net accretion was followed by a 12-year period extending from 1996 to 2008 with a net rate of accretion of only 10 km^2 $year^{-1}$. The higher rate of accretion of 30 km^2 $year^{-1}$ for the period 1984–1996 coincides with the arrival in the estuary of the sediment wave generated by the Assam earthquake, as indicated by Sarker (2009). During this period, net sediment deposition was mainly concentrated in the Patuakhali and Noakhali districts (Fig. 7). The net rate of accretion of about 14 km^2 $year^{-1}$ at Patuakhali was greater than the rate (11 km^2 $year^{-1}$) at Noakhali. This is the only period when net accretion occurred at Patuakhali and during the preceding and following periods there was net erosion in this area. The locations of the areas of net accretion are very close to the flow and sediment outlets of the Ganges-Brahmaputra systems through the Lower Meghna and Shahbajpur channels, but not the locations where the tidal circulation process favours sediment deposition.

The location of the accretion and the time of arrival of the sediment wave in the estuary indicate that the huge amount of fine sand mainly contributed to the high rate of land development at Patuakhali and south of Noakhali between 1984 and 1996. During the same period, the width and size of the North Hatiya Channel reduced considerably. Sokolewicz & Louters (2007) indicated that the decline of the Hatiya Channel between the mid-1980s and the 1990s might be related to the arrival of the sediment (sand fraction) wave in the Meghna Estuary, as proposed by Sarker & Thorne (2006). The water width reduced from 12 km to 6 km between 1984 and 1996 and the corresponding reduction of flow area below the adjacent tidal plain was about 40%

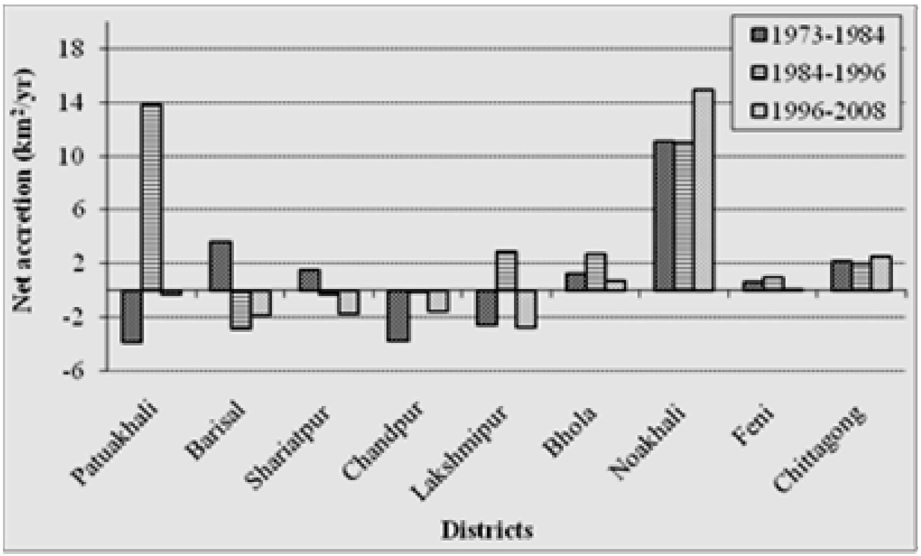

Fig. 7 The spatial distribution of erosion and accretion in the erosion/accretion process.

(CEGIS, 2010). Subsequently, the flow area of the Shahbajpur Channel increased by a similar magnitude (MESII, 2001).

The decline of the Hatiya Channel caused the water level to rise in the Shahbajpur channel and further upstream in the Lower Meghna River at Chandpur. Analysis of the available data shows that the mean daily water level during the monsoon period increased to 0.5 m from the mid-1980s to the end of the 1990s at the right bank of the Shahbajpur Channel, just west of the Hatiya Channel off-take. The increase in water level however, was decreased upstream and it was about 0.3 m at Chandpur. This increase of water level might contribute to the prolonged flood in 1998 and 2004. The high water level at Chandpur, the main outlet of the flood water, may have caused the delaying of the passage of flood in 1998. A recent study of IWM (2009) suggests that the size and net flood of the Hatiya Channel increased in the late 1990s. It is likely that after the passing of the sediment wave, the temporary blockage of the channel has been removed, which may restore the flood carrying capacity of the Lower Meghna River.

The present rate of net accretion, after the diminishing of the effect of the Assam earthquake, is better represented by the net accretion rate (10 km^2 $year^{-1}$) during the period from 1996 to 2008. A comparison of bathymetric surveys undertaken in 1997 and 2000 in the Meghna Estuary suggests a net deposition of 100 million m^3 of sediment per year (MESII, 2001), which may develop 12 km^2 of land, considering that 8 m of sediment deposition would be required to cause land development in the Meghna Estuary (SSSU, 2002). This assessment is based on the average bed and land levels estimated from different bathymetric and land surveys in the Meghna Estuary. The estimates of net land development in the estuary at the end of the 1990s based on satellite images and also on the sediment deposition documented by two successive bathymetric surveys, yield very similar results.

This net accretion rate of 10 km^2 $year^{-1}$ is almost double the long-term average rate of net accretion. This increase is likely to reflect an increased sediment input due to intensive agricultural practices and restriction of sediment deposition in the flood plain and tidal plain due to construction of flood embankments and coastal embankments. These two factors (other than the Assam earthquake) may have increased the sediment supply to the estuary causing the higher rate of net accretion in recent decades. An efficient tidal circulation process, depending on the bathymetry and planform of the estuary may have also caused the net accretion to increase.

In summary it can be seen that during the last 65 years the Meghna Estuary has gained a net amount of 1700 km^2 of land, to which the Assam earthquake was the main contributor. It had a very pronounced impact on the morphology of the estuary. It modified the pattern of the distributary channels in the estuary and most importantly, increased the net accretion rate several fold. There were two phases of net accretion – the first was the very rapid accretion immediately after the earthquake due to the sudden increase of the supply of fine sediment (silt and clay). This phase probably continued until the early 1970s and in that period the net accretion rate was about 46 km^2 $year^{-1}$. The second phase with a high accretion rate occurred from the mid-1980s to the mid-1990s, due to the arrival of the sediment wave generated by Assam earthquake. During this period the coarser fraction (fine sand) of sediment mainly dominated the process and the rate of net accretion was about 30 km^2 $year^{-1}$. During this period, most of the accretion was concentrated in the Patuakhali and Noakhali districts. These locations differed from the locations favoured by the tidal circulation process. Analysis of information on erosion and accretion for the period 1996 to 2008 shows that the net rate of accretion was reduced to 10 km^2 $year^{-1}$, indicating a diminishing effect of the Assam earthquake (Sarker, 2009). At present, insufficient time has elapsed since the earthquake to provide a reliable assessment of the current accretion rate without the effect of the earthquake. However, it can be estimated to be the same as it was during the preceding decade. Intensive agricultural practices, deforestation, construction of flood embankments and coastal embankments have contributed to a higher rate of net accretion than that of long-term net accretion.

With the increase in sediment input after the earthquake, the estuary had become very dynamic causing thousands of people to suffer every year. On the other hand, land reclamation is facilitating the rehabilitation of erosion victims, although the value (price and productivity) of newly accreted land is much less than that of mature tidal plains.

EFFECTS OF SEA LEVEL RISE

The range of the uncertainties associated with the potential rise of sea level in the coming decades is high. Only the effect of sea level and climate change on the Meghna Estuary will be addressed below. With the increase in sea level, the main impact on the estuary will clearly be governed by the water and sediment input from upstream through the Ganges and Brahmaputra rivers. However, these two parameters are highly variable with time and strongly influenced by climatic (precipitation) and anthropogenic forces (Xu *et al*., 2007). Higher sediment flux is generally expected due to higher rainfall and temperature (Walling & Webb, 1996; Hovius, 1998; Zhu *et al*., 2008). According to Goodbred & Kuehl (2000), during the early Holocene period when the monsoon was wetter than at present, the rate of sediment deposition in the Bengal delta was two and a half times higher than that of the present day. Most of the large rivers in the world are greatly affected by human activity (dams and water diversions), resulting in the reduction of water and sediment supply to the sea (Xu *et al*., 2007). The extent of human impact and its effects on the fluvial discharge of the Ganges and Brahmaputra rivers is also uncertain. A higher rate of discharge and sediment flux proportional to the increase of precipitation in the Ganges and Brahmaputra basins would seem to be a likely scenario for the coming decades.

A number of studies have been carried out to assess the impact of sea level rise and flooding in Bangladesh (WARPO, 2005; IWM & CEGIS, 2007; Yu *et al*., 2010). In these studies flooding due to sea level rise was assessed by a numerical model simulation, assuming that the level of the river and estuary bed and the flood plain and tidal plain will remain the same. Brammer (2004) suggested that sediment deposition will raise the land in the coastal areas and the banks of the tidal and estuarine rivers at the same rate as the rise in sea level, if the rate of sea level rise is limited to a certain low range. However, flooding will be increased on the land behind the raised coastal land and higher river banks due to ponding of rain water.

A recent study of CEGIS (2010) indicated that with a sea level rise of 60–100 cm within the next 100 years, there would not be any transgression of the sea if sediment supply remains the same. The vertical accretion of land in the estuary would keep pace with the sea level rise. But the riverbank adjustment would have a phase lag depending on the distance from the bay. However, the major part of the tidal plain in Bangladesh will not receive any sediment and will suffer from drainage problems. The formation of new land in the Meghna Estuary would be continued at a lower rate, depending on the rate of sea level rise.

ISSUES OF SEDIMENT MANAGEMENT

There is a popular belief that construction of cross-dams at the end of the 1950s and early 1960s had caused the accretion of several hundred km^2 of land. People like to believe that construction of cross-dams connecting islands with the mainland could again facilitate major accretion in the Meghna Estuary. However, this fails to take account of the fact that the rate of net accretion was high during the 1950s and 1960s only because a huge amount of sediment supplied by the landslides caused by the 1950 earthquake was moving back and forth in the estuary and being deposited in the depositional environment. Now sediment input to the estuary has been reduced and the rate of net accretion has slowed down. Construction of cross-dams will not increase the net accretion dramatically. It may rather connect water locked islands with the mainland. The additional accretion of land around the cross-dams would cause net accretion or erosion at other locations in the estuary.

In addition to intervening in the Meghna Estuary to promote lateral accretion, emphasis should be placed on enhancing the vertical accretion. The polders embanked in the 1960s and 1970s have been deprived of sediment for the last 40–50 years. These polders constitute a major part of the tidal plains in Bangladesh. Being part of a delta, subsidence due to compaction will clearly occur. However, sea level rise will make these polders highly vulnerable to drainage problems. In the coming decades, pumping out rain water from polders will be very costly. Injecting sediment into the polders will be a good strategy for adapting to sea level rise. Equally, diversion of the sediment laden flow far into the flood and tidal basins would be able to reduce deep flooding. Bringing the tide (mixture of water and sediment) into the polders for improving the drainage capacity of the tidal rivers has been undertaken for a decade in the southwest region of Bangladesh. The method of injecting the sediment would be different for different locations, and this would mainly be governed by the characteristics, availability and dispersion processes of the sediment within the area concerned. This would be in line with the popularly accepted '*no regret strategy*' for adapting to climate change. It implies that if there is no sea level rise in the coming decades, injecting sediment into the polders would still compensate for delta subsidence and moreover, the sediment would enrich the nutrient status of the soil.

CONCLUSION

The effect of the 1950 Assam earthquake and human activity on the Meghna Estuary has been studied using historical maps, satellite images and information and knowledge gathered from previous studies. There are uncertainties due to inaccuracies in the historical maps and in the delineation of shorelines from satellite images. However, the changes in the estuary over time have been so enormous that the magnitude of any potential errors may not significantly influence the findings. From 1776 to 1943, the net accretion rate in the Meghna Estuary was about 5 km^2 $year^{-1}$. This level of accretion is very close to the long-term accretion rate of the Bengal delta. The Assam earthquake of 1950 caused huge landslides in the Himalayas, which discharged billions of cubic metres of sediment into the Brahmaputra River in India. The fine fraction of this sediment (silt and clay) reached the estuary within a few years and until the early 1970s caused the net accretion of about 1100 km^2, resulting in a net accretion about 46 km^2 $year^{-1}$. The coarser fraction of the earthquake-derived sediment moved through the river system more slowly and probably reached the Meghna Estuary during the mid-1980s and again increased the net accretion to 30 km^2 $year^{-1}$. After the effect of the Assam earthquake diminished, the prevailing rate of net accretion in the estuary reached about 10 km^2 $year^{-1}$. This rate remains higher than the long-term accretion rate within the Meghna Estuary, probably reflecting the effect of the change in land-use within the catchments of the Ganges and Brahmaputra rivers and construction of flood embankments and coastal polders.

During the last six decades the Meghna Estuary has gained a net land area of about 1700 km^2. This high accretion rate will not be maintained (unless there is another event delivering huge amounts of sediment occurs), because the effect of the Assam earthquake has already diminished. Sea level rise in the future, due to climate change, may also require more sediment to produce the same extent of land accretion. For the predicted rate of sea level rise, for example 60–100 cm in the next 100 years, transgression of the sea in the Meghna estuary is not expected, if the sediment supply from the upstream remains the same. In this situation, the rate of vertical accretion in the estuary would keep pace with the sea level rise. However, polder areas within the tidal and estuarine plains will not get any benefit from further sediment input from upstream unless a method of planned and effective sediment injection into the polders is adopted. Emphasis should be placed on vertical accretion, rather than lateral accretion, to provide an effective adaptation strategy against sea level rise due to climate change.

Acknowledgements This study relied greatly on the historical maps and satellite images contained in the CEGIS archives. The authors have enjoyed generous support from Mr Giasuddin Ahmed Choudhury, Executive Director, CEGIS during the study. The assistance of Mr Sonkor Chandra Sinh and Ms Asifa Rahman of CEGIS for graphics and editorial support, respectively, is highly appreciated.

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