Sustainability of the coastal zone of the Ganges-Brahmaputra-Meghna delta under climatic and anthropogenic stresses

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Abstract

The Ganges-Brahmaputra-Meghna (GBM) delta is one of the world's largest deltas. It is currently experiencing high rates of relative sea-level rise of about 5 mm/year, reflecting anthropogenic climate change and land subsidence. This is expected to accelerate further through the 21st Century, so there are concerns that the GBM delta will be progressively submerged. In this context, a core question is: can sedimentation on the delta surface maintain its elevation relative to sea level? This research seeks to answer this question by applying a two-dimensional flow and morphological model which is capable of handling dynamic interactions between the river and floodplain systems and simulating floodplain sedimentation under different flow-sediment regimes and anthropogenic interventions. We find that across a range of flood frequencies and adaptation scenarios (including the natural polder-free state), the retained volume of sediment varies between 22% to 50% of the corresponding sediment input. This translates to average rates of sedimentation on the delta surface of 5.5 mm/yr to 7.5 mm/yr. Hence, under present conditions, sedimentation associated with quasi-natural conditions can exceed current rates of relative sea-level rise and potentially create new land mass. These findings highlight that encouraging quasi-natural conditions through the widespread application of active sediment management measures has the potential to promote more sustainable outcomes for the GBM delta. Practical measures to promote include tidal river management, and appropriate combinations of cross-dams, bandal-like structures, and dredging.

Keywords: Ganges-Brahmaputra-Meghna delta, anthropogenic climate change, relative sea-level rise, sedimentation, sustainability.

1. Introduction

Lying at the transition between fluvial and coastal environments, deltas are dynamic environments that are changing constantly due to both climatic and anthropogenic factors (Ericson et al., 2006; Tessler et. al., 2015; Santos and Dekker, 2020). With an abundant supply of nutrients associated with fine-grained sedimentation, deltas therefore often have highly productive soils for agriculture and fisheries, as well as ease of transport, so they have long been attractive places for human settlement, urban development, and intensive economic activity (Woodroffe et al., 2006; Syvitski et. al., 2009; Edmonds et al., 2020). However, many deltas are now experiencing severe anthropogenic stress (Nicholls et al., 2020; Vasilopoulos et al., 2021) resulting from, for example, the construction of upstream dams, the development of dikes and embankments, water and mineral extraction, habitat destruction, and significant land-use change. These interventions frequently perturb natural water and sediment dynamics, which results in promotion of land subsidence, salinity intrusion, water quality deterioration, and the reduction of accretion processes (Day et. al., 1997; Nicholls et al., 2018; Rahman et al., 2020). In addition, climate-driven sea-level rise (SLR) further compounds the multiple stresses that contemporary deltas are facing (de Souza, 2015; Brown et al., 2018).

The Ganges-Brahmaputra-Meghna (GBM) delta, located at the northern margin of the Bay of Bengal, is administered by both India and Bangladesh. It is characterized by many livelihood opportunities, as well as biophysical and socio-economic challenges which are increasing due to rising climate and anthropogenic stress (Rahman et al., 2020; Marcinko et al., 2021; Das et al., 2021). The large input of freshwater, sediments, and nutrients, combined with the high saline water input forced by tides, underpin diverse ecosystem resources (Miah, 2010; Nicholls et al., 2018). The people living in the coastal belt are highly dependent on traditional monsoon rice cultivation, as well as activities such as riverine and marine fishing and honey collection. The coastal population is also exposed to climate hazards such as fluvio-tidal floods, and tropical cyclones accompanied by storm surges, as well as riverbank erosion, salinity intrusion due to seasonal low flow levels in rivers, upstream water diversions and land use impacts (Dastagir, 2015; Akter et al., 2019). The mean tidal range in Bangladesh varies from 3-4 m and the tide propagates up to 100 km inland (Choudhury and Haque 1990; Haque and Nicholls, 2018; Bricheno et al., 2016), yet the delta's low-lying areas have an average elevation of just 1-2 m above mean sea level, creating a situation where large areas of land are exposed to natural inundation. In addition, large areas of the delta are subsiding at 2-3 mm/yr (Brown and Nicholls, 2015; Becker et al., 2020), further contributing to the submergence of the low-lying areas of the coastal zone.

Until the 1950s, the tidal floodplain in the GBM delta (in Bangladesh) was strongly connected to the river system, so that it functioned as a natural sedimentation basin. Local communities managed the floodplain through construction of temporary low height earthen embankments during the eight dry months of the year (Gain et al., 2017) to protect crops against salinity intrusion. These temporary embankments were submerged during the monsoon flooding, thus enabling quasi-natural inundation and sedimentation processes on the tidal floodplains. Additionally, these quasi-natural processes allowed hydrological flows, sediment dispersion and elevation gain as part of the delta building process. However, during the 1960s-1990s, 139 polders (that include more than 6000 km of earthen embankments) were constructed to protect the land from salinity and flooding as part of an attempt to increase agricultural productivity, and as a result contemporary land use within the poldered areas has become increasingly dependent on dike protection. Therefore, the sediment inputs and sediment dispersion processes on the delta floodplain are now significantly changed. Importantly, in areas where natural sedimentation has been disrupted, the polders lose elevation relative to sea level which increases the threats of waterlogging, saline groundwater intrusion and catastrophic damage if the dikes are breached. The rate of accretion in what is today a highly modified GBM delta depends on how much incoming fluvial and/or marine sediment flux is retained on the delta surface. The physical sustainability of the delta depends on the future rate of fluvial sediment supply (Darby et al., 2018; 2020) and its dispersion processes (Wilson et al., 2017) through the channel networks that intersect the delta surface. Recently, Dunn et al (2019) showed that the supply of fluvial sediment to the GBM delta is likely to decline significantly in the future due to anthropogenic changes in the upstream catchment.

If fluvial sediment supply declines, vertical accretion and its capacity to counter subsidence and SLR is also likely to decrease (Rahman et al., 2018; Dunn et al, 2018), potentially causing large areas of the delta to progressively lose elevation, which is especially problematic for low-lying areas. This poses a substantial and increasing hazard to the large rural population and their livelihoods as the elevation of the delta surfaces they inhabit approaches, or falls below, mean sea level. Therefore, it is fundamental to understand the changing trends of relative sea-level rise (RSLR = local rate of SLR + land subsidence) and the rate of delta plain sedimentation (Day et al., 2008). It is widely recognized (Nowreen et al, 2014) that the non-functionality of canals within poldered areas restricts flow and sedimentation and is, therefore, responsible for sedimentation of riverbeds in the region outside the polders. The gradual fall of elevations inside polders due to the absence of sediment input has created uneven elevations inside and outside of the polders, which promotes water-logging-related problems (Noor, 2018). If saline water enters poldered regions during cyclones, salinisation can occur for a prolonged period. As such, there is growing interest in evaluating potential remedial measures including: (i) the restoration of the tidal plain functioning, and (ii) promoting sediment ingress and retention into polders to raise the low-lying land, consistent with nature-based approaches.

Before adopting such options, it is fundamental to understand how anthropogenic factors are changing and what impacts those factors will have on delta functions. There are few system-level analyses that address these issues, such as Rogers and Overeem (2017) who undertook numerical simulations of the GBM delta using AquaTellus. However, the detailed hydrodynamics of the processes involved are not well represented. In particular, the AquaTellus model cannot resolve the impacts of polders on overbank flooding and resultant sediment deposition. In another study, a process-based, two-dimensional numerical model using the Delft3D modelling platform was applied to undertake a range of simulations designed to elucidate the impact of environmental changes and anthropogenic interventions such as fluvial water discharge, sediment discharge, relative sea level rise, construction of polder-dykes and cross-dams (Angamuthu et al., 2018). One of the study objectives was to understand the dynamics of the delta morphology over multi-decadal timescales. It was observed that when individual drivers of change act in combination, delta building processes such as the distribution of sediment flux, aggradation, and progradation are disrupted by the presence of isolated interventions that eventually lead to growing dependence on flood defenses and increasing impacts if they fail. In this context, the aim of this paper is to quantify the sedimentation across the surface of the Ganges-Brahmaputra-Meghna delta and assess its potential to counter RSLR. To do this we employ a large-scale numerical model to investigate the potential for sedimentation across the delta for plausible combined scenarios of flooding and human intervention on the delta. In contrast to the prior studies, these new simulations provide a more robust and realistic representation of the hydrodynamic processes in the presence of polders.

2. Methodology

2.1 Study Area and Methodological Framework

The GBM basins and delta, with flows of water and sediment coming from the basins and draining through the estuarine networks in the coastal region, are shown in Figure 1. Eastern, central, and western region of the estuarine system (henceforth EES, CES, and WES, respectively) are recognized, connected through several cross channels. In addition, the seasonal variations of freshwater flow cause local variations in water and sediment flows that ultimately lead to spatial and temporal variations of sedimentation within the estuarine system (Haque et al., 2016; Dasgupta et al., 2014).

Figure 1**:** *River basins of the Ganges-Brahmaputra-Meghna and the estuarine systems of coastal Bangladesh. The inset figure shows the entire basins of the three major rivers – the Ganges, Brahmaputra, and Meghna. The zoomed view, as marked in the inset, shows the part of the basins which are in Bangladesh and the three estuarine systems – Western Estuarine System (WES), Central Estuarine System (CES) and Eastern Estuarine System (EES). The important rivers (Ganges, Brahmaputra-Jamuna, Meghna, Gorai, Arial Khan, Mathabhanga, Madhumati), estuaries (Lower Meghna system), and connecting channels (Beel Route, Spill Channel-1, Spill Channel-2, Spill Channel-3, Ghashiakhali) within these estuarine systems are also shown. Four locations where sedimentation thickness was measured by Rogers et al. (2013) in the Sundarban region are shown by square box symbol, where location-1 is in Bagerhat district, location-2 is in Pirojpur district, location-3 is in Khulna district, and location-4 is in Satkhira district.*

We seek to clarify the formative processes of the GBM delta system via quantification of the key parameters including SLR, subsidence, total incoming sediment, and its retention on the delta surface. With respect to quantification of the retention of sediment on the delta surface, we evaluate sediment dispersion processes, including estimation of the portion of incoming sediment load contributing to delta building and maintenance, and tidal floodplain sedimentation, using empirical data complemented by numerical experiments. The overall analytical framework enables the determination of effective sea-level rise (ESLR) in terms of vertical change of delta surfaces compared to local relative sea-level rise (RSLR) as defined by Equation (1):

$$\mathrm{ESLR} = \mathrm{RSLR} - \mathrm{A} \quad (1)$$

where A is the aggradation rate determined from the volume of sediment retained on the subaerial delta surface as new sedimentary layers (Syvitski et al., 2009) in mm/yr, and $\mathrm{RSLR} = \Delta E + \mathrm{NS}$, where ΔE is the eustatic SLR (mm/yr) as determined from changes to the volume of the global ocean over time, and net subsidence (NS) is defined as $\mathrm{NS} = \mathrm{CN} + \mathrm{CA} \pm M$ (with CN = natural compaction, CA = accelerated compaction that reduces the volume of deltaic deposits, and M = vertical movement of the land surface as influenced by the redistribution of Earth's masses). Therefore, positive values of ESLR in Equation (1) indicate a tendency for land submergence whereas negative values indicate the potential for emergence of new land.

Although attempts have been made recently to estimate the above parameters for a comparative risk assessment across different deltas (Tessler et al., 2017), analysis of specific deltas remains problematic because of the need to consider the effects of local infrastructure, such as the polders in coastal Bangladesh. Information on SLR and subsidence is available from the literature, but quantification of the retained portion of incoming sediment flux and its distribution on the delta surface is still an issue that needs to be systematically resolved. We therefore applied the morphological model of the Delft3D modeling suite to compute coastal floodplain sedimentation under four hydrological and anthropogenic scenario combinations (Hibma et al. 2003; Haque et al., 2016; WARPO-BUET, 2019), with field observations of sedimentation (Rogers et al., 2013; Rogers and Overeem, 2017) used for model calibration and validation.

The delta-surface sedimentation for each of these scenarios is then calculated in conjunction with estimates of sea-level rise and subsidence to evaluate effective sea-level rise for each scenario.

2.2 Assessment of Sedimentation

To assess the aggradation rate (A in Equation (1)), the two-dimensional module of the Delft3D flow and morphology model is applied to estimate the retained volume of sediment and the area of the inundated subaerial delta surface. The Delft3D morphology model is dynamically coupled with the flow model, therefore any changes in the river and floodplain morphology that affect the flow field and vice versa are simulated. We have selected a two-dimensional model over one-dimensional (*which considers flow as unidimensional and does not consider momentum transfer between the river-floodplain systems*) and three-dimensional (*which is more relevant to resolve the local flow dynamics in detail*) to accommodate dynamic interaction between the river and floodplain systems, lateral dispersion and diffusion processes, and floodplain sedimentation. The two-dimensional module of Delft3D is widely used, with a long track record in different environments including oceans, coastal environments, estuarine and river systems all over the world (Thanh et al., 2019; Sandbach et al., 2018; Hu et al., 2018; Salehi, 2018; Li et al. 2018; Bennett et al., 2018) including many applications in Bangladesh (Haque, et al., 2016; WARPO and BUET, 2019; Akter et al., 2019; Al Azad et al., 2018; Haque et al., 2018).

2.2.1 Model Description

The model domain consists of the coastal region of Bangladesh that includes land, river, and sea area (Figure 2). The model is bounded in the north by the major rivers of the system (Ganges, Brahmaputra, and Meghna) and in the south by the Bay of Bengal (Figure 2). A variable mesh size is used with a coarser grid size (approximately 500m × 600m) in the sea area and finer grid size (approximately 200m × 300m) in the land area to capture the details of river, estuary, and land topography. All the rivers and estuaries within this region which have a width greater than or equal to 100m is included in the model domain. The coastal zone contains 139 polders, of which 103 are located within the study region based on the polder map available from the National Water Resources Database (NWRD) of WARPO. The locations of polders with actual and design dike heights are provided in the supplementary material (Figure S1).

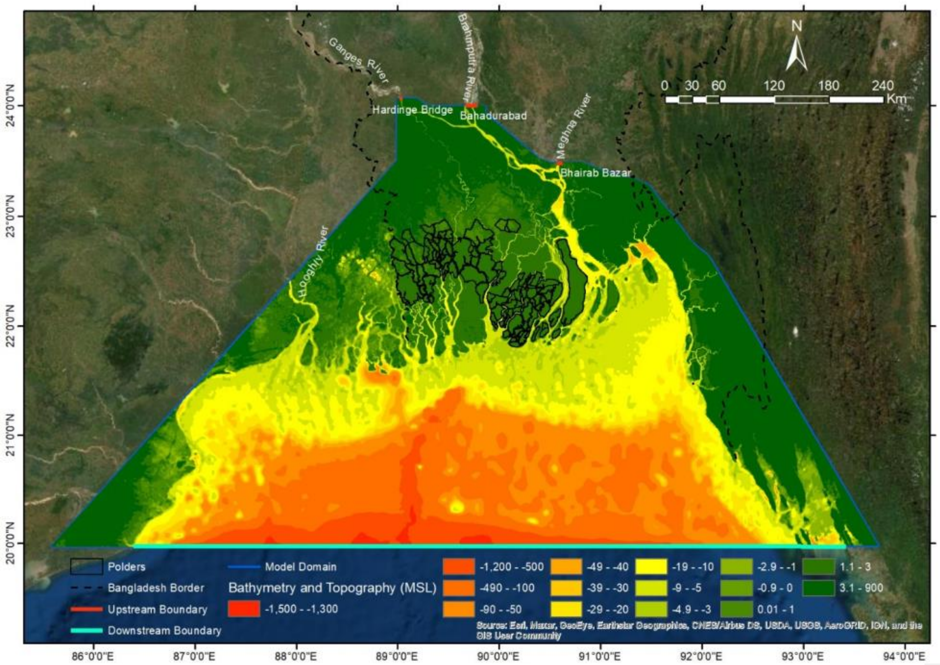

Figure 2: *The model domain, including the major rivers, topography and bathymetry. The topography and bathymetry are measured in meters from Mean Sea Level (MSL). The model domain covers the coastal part of the Ganges-Brahmaputra-Meghna delta, and the Bangladesh territory is shown by black dotted lines. Locations of the three upstream river discharge boundaries and the downstream sea level boundaries are marked. The black firm lines represent the polders.*

The model parameters which are used during model simulations are: (1) Manning's resistance coefficient; (2) sediment density; (3) water density; (4) median sediment size; (5) hindered and non-hindered settling velocities; (6) vertical diffusion coefficient; (7) sediment concentration and concentration gradient in the bottom layer; (8) erosion parameter; and (9) critical shear stress for erosion and deposition.

During model simulations, the different size fractions of sediment, including mixtures of non-cohesive and cohesive sediments, are considered. Based on Rogers and Overeem (2017), the distribution of cohesive and non-cohesive sediments was selected as 70% cohesive and 30% non-cohesive for this study region. In all the numerical experiments, two contrasting flooding conditions were used – an 'average' and an 'extreme' flood condition. For the average flood condition, measured data at the three upstream boundary locations (Figure 2) were used for the year 2000 (January 1 to December 31). For the extreme flood condition, measured data were used for the year 1998 (January 1 to December 31).

Details of the model is provided in the supplementary material as: model equations for the water and sediment transport processes (Section S.1), model data sources (Section S.2), model boundary conditions (Section S.3), model parameters (Section S.4), values of the calibration parameters (Table S1), and values of the model parameters used in the numerical experiments (Table S2).

2.2.2 Model Calibration and Validation

The only sedimentation data available for model calibration is from Rogers et al. (2013) for the Sundarbans. During model calibration, constant values were used for the following model parameters across the entire model domain: (1) water and sediment properties; (2) settling velocity of cohesive sediment; (3) maximum sediment concentration for hindered settling; (4) bottom layer thickness; (5) erosion parameter; and (6) critical shear stress for erosion and deposition. However, these values may vary to an unknown extent in the other regions of the coastal zone, so during calibration we applied uncertainty ranges to the following spatially variable parameters: (1) space-varying resistance coefficients; (2) space varying diffusion coefficients; (3) space varying sediment concentration; and (4) concentration gradients. These parameters largely dictate the flooding and sedimentation processes across the study area. The resistance co-efficient is the dominant model parameter determining the spatial variability of flow and sedimentation processes. Manning's co-efficient is used in the model as the resistance coefficient and is varied in this study from a minimum of 0.00025 in the ocean to a maximum of 0.10 in the Sundarbans region (see the supplementary material, Table S1). Ocean is a wide water body where bottom resistance has little influence to flow and sedimentation processes (resistance co-efficient = 0.00025). Resistance slowly increases towards the estuary and rivers (varies from 0.015 to 0.025). Floodplain flow and sedimentation processes are largely influenced by the land-use types, which are represented by a variable resistance coefficient (0.025 close to estuary/river and increasing to 0.040 further inland). Depending on the forest cover, flow velocity decreases in the Sundarbans region. Denser forest cover is used near the coast (resistance coefficient = 0.1) to a lighter forest cover more inland (resistance coefficient = 0.08). The diffusion coefficient determines the turbulent transport of suspended sediment (Equation S1 in the supplementary material). Spatial distribution of suspended sediment concentration is not available in the study area. To take account of this uncertainty, we employed a spatially varying diffusion coefficient between 1-10 m^2/s, which ensures the optimal calibration result (supplementary material, Table S1). Solution of the transport equation (Equation S1 in the supplementary material) with this diffusion coefficient gives space varying suspended sediment concentrations and concentration gradients for the entire study region. Values of all the model calibration parameters used here are summarized in the supplementary material (Table S1).

The model was calibrated using field data from March-October 2008 (Rogers et al., 2013), as shown in Figure 3. Two different methods were used to calculate sedimentation during this calibration period:

(a) Method-1: Annual sedimentation based on the simulation from March-October (monsoon season), following Rogers et al. (2013).

(b) Method-2: Annual sedimentation based on a simulation for the whole year (monsoon and dry seasons).

Except for location-4, Method-1 performs better than Method-2 (Figure 3), which means that the model performs better when the same time period is applied in the model to that which is used in the field (Rogers et al., 2013). Sedimentation is generally low in Method-2 (the 12-month simulation) compared to Method-1 (8 months of simulation from March to October i.e. during the monsoon) except for location-3. Method-2 includes the dry season period when erosion is dominant over sedimentation due to the low sediment inflow into the system and regular tidal flooding on the floodplain. Location-3 (located in Khulna district, see Figure 1) receives more sediment due to the clockwise residual circulation pattern in the Bay of Bengal near the coast generated from the Coriolis force (Haque et al., 2016). Although Method-1 performs better in the context of model calibration, in this study we have used Method-2 to simulate annual sedimentation in the study region to also consider the effects of the dry season.

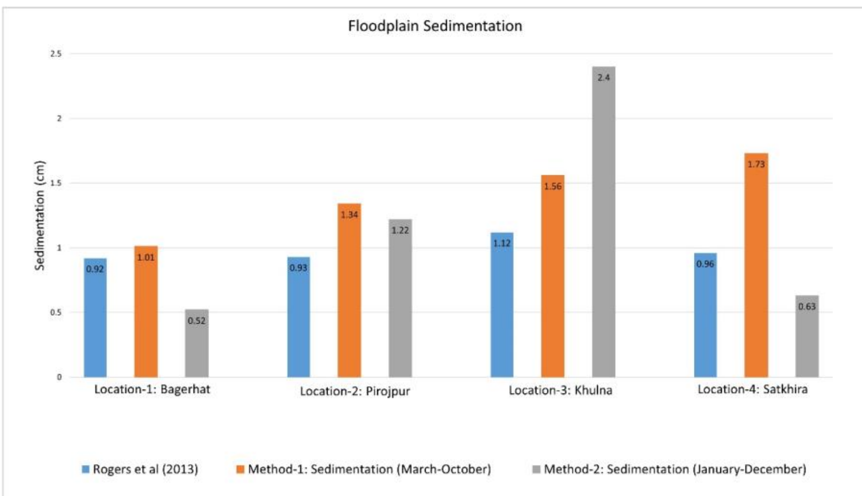

Figure 3: *Comparison of floodplain sedimentation in the Sundarban region between modelled and measured data (Source of measured data: Rogers et al., 2013). All the measurement locations are in Sundarban region (see Figure 1). Location-1 is in Bagerhat district, location-2 is in Pirojpur district, location-3 is in Khulna district, and location-4 is in Satkhira district. Method-1 shows the sedimentation for 8 months model simulation (March-October) whereas, Method-2 shows the sedimentation for 12 months model simulation (January-December). Both the measurement and the model simulations are for the year 2008.*

To validate the model, the simulated sediment load deposited on the floodplain was compared with estimated data (keeping all other data, parameters, and assumptions unchanged from the values used during the model calibration in Method-2). Goodbred and Kuehl (1998) and Allison (1998) estimate that 30-40%

of the total sediment entering the system is deposited over the floodplain. Although these two studies are not specific for any flood condition, for model validation we compared the model simulation for average flood conditions with their estimated value due to absence of any other data. Specifically, the percentage of sediment load deposited over the different floodplain systems (WES, CES and EES, see Figure 1) and the total sediment load computed for the entire study region is shown in Table 1. Out of a total sediment load of 400 Million Tonnes entering the system during an average flood year, 90 Million Tonnes (~22%) are deposited on the floodplain of the study region according to the model. The WES is predicted to receive the greatest portion, followed by the CES and EES. The fact that the model predicts a higher retention potential for the CES over the EES is realistic due to the absence of polders in the central region, which allows greater sedimentation. The high retention for the WES reflects that sediment is readily trapped inside the high resistance Sundarbans Forest system where polders are completely absent.

Table 1: *Comparison of model-simulated retention of sediment on the delta plain and observations of Goodbred and Kuehl (1998) and Allison (1998) during an average flood year. The delta plain is divided into three estuarine systems – Western Estuarine System (WES), Central Estuarine System (CES), and Eastern Estuarine System (EES). All sediment loads are expressed in Million Tonnes (MT).*

Total sediment input (MT)		400
Tidal floodplain region	Sediment load deposited (MT)	Approximate percentage of total load retained
WES	46	11%
CES	27	7%
EES	17	4%
Total (Model)	90	22%
Total (Goodbred and Kuehl, 1998; Allison, 1998)	124 to 165	30% - 40%

2.2.3 Outline of the Numerical Experiments

In this study, simulations using the Delft3D flow and morphological models were used to compute the impacts of polders on floodplain sedimentation in the study area. Four numerical experiments were conducted, categorized broadly as two states of the system: a 'natural state' and an 'intervened state' under two different flooding conditions – an 'average flood' with a return period of 2.33 years and an 'extreme flood', with a return period of 200 years. The 'natural state' represents the physical setting when there is no human intervention in the system. The 'intervened state' represents the physical system with the existing polder embankments constructed in the system. Further, the 'average flood' represents a flood condition when 20% to 22% of the total floodplain in the country is inundated, while the 'extreme flood' represents a flooding condition for which more than 60% of the total floodplain is inundated (BWDB, 2015).

2.3 Assessment of Sea-Level Rise and Subsidence

We compiled sea-level rise data for the Bay of Bengal region from global sources and used an estimate consistent with values used in in Bangladesh national planning. Presently, climate-induced sea-level rise is ~ 3 mm/year and subsidence is ~ 2 mm/year, giving present RSLR as ~ 5 mm/year (Brown and Nicholls, 2015; Becker et al., 2020). This RSLR value is used as a reasonable estimate of the minimum future value in the GBM delta (BDP 2100, 2018; IPCC, 2019) and is compared with the sedimentation thickness obtained from the numerical experiments using Equation 1.

3 Results

3.1 Numerical Experiments-Group 1: Flooding and Sedimentation in an Intervened State

In the 'intervened state', we modelled two scenarios of inundation and corresponding sedimentation reflecting the average (Figure 4a and 4c) and extreme flood conditions (Figure 4b and 4d). Sedimentation occurs in those parts of the floodplain where sediment-laden flood water can enter. During a flood event, water can only enter a polder when the water depth outside the embankment exceeds the specified embankment height. Only a few of the polder embankments in the north of the region are overtopped during the average and extreme flood conditions (Figures 4a and 4b). Indeed, no polders at all are overtopped in the central region (part of CES) or in the Sundarbans (part of WES). In the CES region during average flood conditions, inundation and sedimentation are confined within the low elevation area (Figures 4a and 4c). In the same region, both inundation and sedimentation extend to a larger area during the extreme condition (Figures 4b and 4d). In the Sundarbans region, inundation and sedimentation during extreme flood condition (Figures 4b and 4d) is substantially higher than during the average flood condition (Figures 4a and 4c).

In general, the numerical experiments for this 'intervened' condition highlight the effectiveness of polder embankments in preventing inundation in the region for a wide range of flood conditions. Hence, sedimentation only occurs in the unprotected regions outside the polder embankments and, to a limited extent, in the region where floodwater overtops the embankments. An important observation is that during the extreme flood condition the sedimentation is much higher when compared to the average flood condition (Figures 4c and 4d). The resulting volume of sediment retained on the delta surface during an 'extreme' flood is also higher (~ 500 MT, which is approximately 42% of the incoming sediment during an extreme flood) compared to the 'average' flood condition (~ 90 MT, which is approximately 22% of the incoming sediment during average flood). One of the important hydraulic reasons for such enhanced sedimentation in the extreme flood condition within the coastal zone of Bangladesh is that the sediment transport capacity does not increase proportionately with the increase of water discharge and sediment flow because of the extensive flat land elevations and associated low longitudinal slope. This creates a sediment surplus in excess of transport capacity and therefore, more sediment is likely to be deposited (Haque et al., 2016) with the increase of flow-sediment in the GBM system. However, as the return period for the extreme flood event is large (200 years), it is unlikely that very large magnitude floods contribute significantly to delta building processes in the longer term.

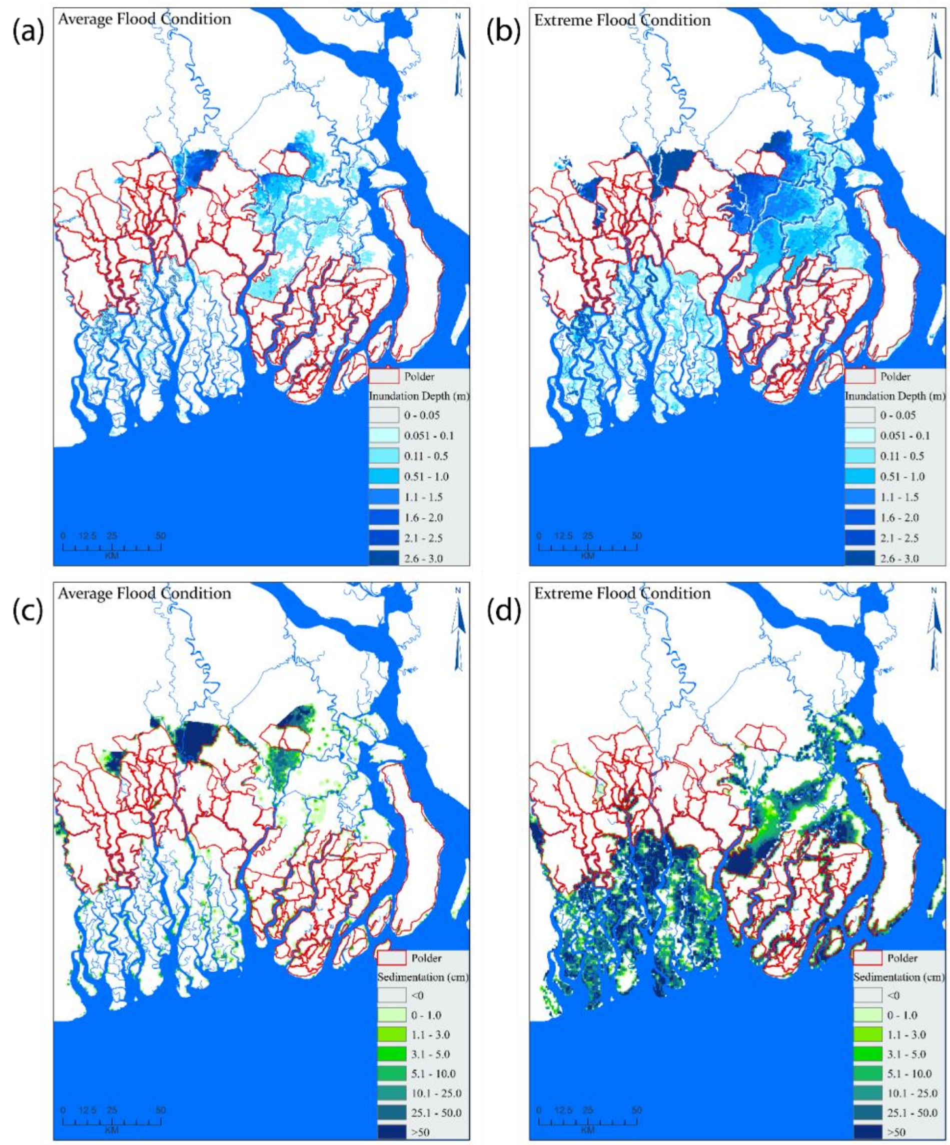

Figure 4: *Maximum inundation (4a and 4b) and annual sedimentation (4c and 4d) in the intervened delta state during average flood and extreme flood conditions, respectively. The red lines show the polder embankments. Only part of the unprotected land is inundated during average flood condition (4a). The*

extent and severity of inundation increases with the intensity of flooding (4b). Sedimentation occurs in the areas which are flooded (4c and 4d). Following the inundation patterns, sedimentation only occurs on part of the inundated land (4c) and increases with the depth and area of inundation (4d).

3.2 Numerical Experiments-Group 2: Flooding and Sedimentation in a Natural State

The numerical experiments represent a pre-disturbance delta, before polders were constructed in the region (pre-1960 condition). All the major, intermediate, and minor rivers and their interconnections are represented as in the present-day condition. This allows fluvial, fluvio-tidal, and tidal flooding in the floodplain of the system to be represented in a hypothetical natural state under present-day conditions. The hydrodynamics and sedimentation in the system are governed by the exchange of flow between the floodplain and riverine/estuarine systems. As expected, the simulations for the natural state show inundation across a wider area for both flood conditions. As sedimentation occurs in the inundated regions, a wider area experiences sediment deposition in the natural state as compared to the intervened state (see Figures 4 and 5). In the numerical experiment for the average flood condition, areas in the natural state are flooded and sedimented (Figures 5a and 5c) which were protected in the intervened state (Figures 4a and 4c). The extreme flood condition shows how effective the polder embankments are in protecting the region against inundation. Without polder embankments, the entire region is inundated during the extreme flood condition (Figure 5b), with a much wider area experiencing sedimentation (Figure 5d). The maximum zone of sedimentation is again found to be in the Sundarbans and its northern area (Figure 5d). The area north of the Sundarbans is well known as a water-logged area due to polder embankments which restrict sedimentation on the floodplain inside the protected region (WARPO and BUET, 2019). This group of numerical experiments show that without these polder embankments, sedimentation would otherwise occur in what is today a sediment-starved floodplain.

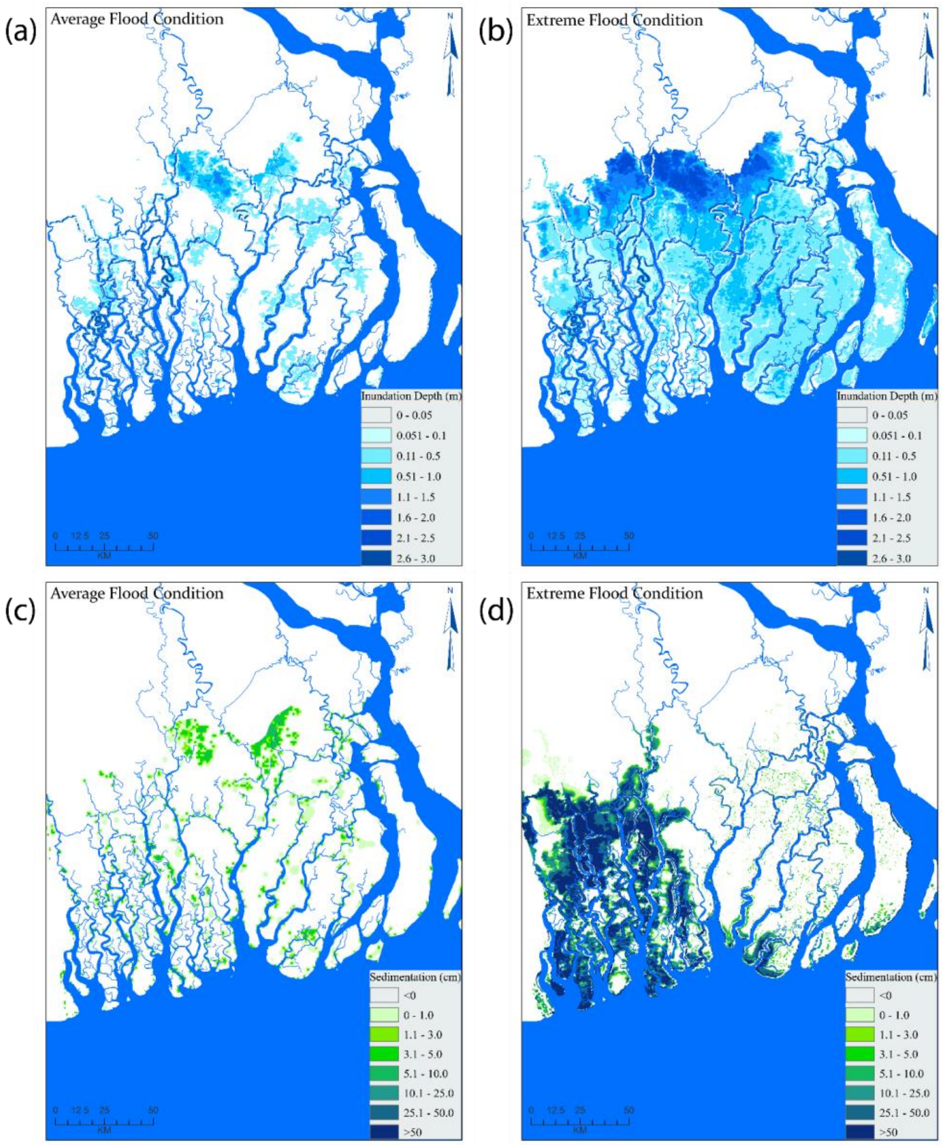

Figure 5: *Maximum inundation (5a and 5b) and annual sedimentation (5c and 5d) in the natural delta state for average flood and extreme flood conditions. The inundation of the delta in the natural state depends entirely on the flooding condition, existing river and canal bathymetry, and land topography: less*

inundation during an average flood condition (5a) as compared to an extreme flood condition (5b). For average flood conditions, sedimentation occurs in the delta region where inundation depth is relatively high (5c). For extreme flood conditions, higher flow resistance in the Sundarban region increases sedimentation (5d).

3.3 Characteristics of Sedimentation on the Delta Surface based on the Numerical Experiments

Basic characteristics of sedimentation on the delta surface are quantified based on two groups of numerical experiments described in Section 3.1 and 3.2. Ranges of yearly average values for different flood conditions and for different physical settings of the delta, as characterized by the following parameters, are computed to describe the characteristics of sedimentation in the delta - total sediment input, sedimented area, sediment retained on the floodplains, and sedimentation thickness (Table 2). The lower value of the range for all the parameters in Table 2 represents the average flood condition, while the upper value represents the extreme flood condition. The range of values also represent different physical settings of the delta (intervened or natural). It is expected that during any flood event and for varying sediment management scenarios in the delta, the values of the parameters will vary in the ranges defined in Table 2. For example, during any flood event, total sediment input in the system varies between 400 MT to 1200 MT depending on the frequency of the flood event (Table 2). Due to this flood event and sediment inflow to the system, total sediment volume deposited in the floodplain varies between 90 MT to 600 MT, which is 22% to 50% of the total incoming sediment volume.

The maximum fraction (30 MT to 340 MT, which is 8% to 28% of the inflow sediment volume) of the sediment is deposited on the CES where there are no polders even during the intervened state of the delta. The next highest area of sedimentation is the WES (45 MT to 260 MT, which is 11% to 21% of the inflow sediment volume) which is dominated by the Sundarbans. Although sediment input is almost similar for the WES and CES, unlike the CES, the WES is a heavily intervened system (except the Sundarbans region) causing uneven distribution of sediments inside and outside the polders. As mentioned in section 3.2, this causes waterlogging in most parts of the WES. Among the three systems, the area of minimum sedimentation is the EES (17 MT to 25 MT, which is 2% to 4% of the inflow sediment volume). The EES and CES are dominated by the freshwater systems of the Lower Meghna while the WES is dominated by the saline water estuarine systems (Figure 1). Sources of sediments in the WES are therefore different from the CES and EES. The WES receives marine sediments which re-enter into the system through oceanic circulation (Haque et al., 2016), while the CES and EES receive riverine sediments from the Lower Meghna system (Figure 1). These aspects determine the non-uniform spatial variation of sediment distribution in the delta, resulting in variations of sedimentation thickness on the delta surface (5.5 mm to 7.5 mm) that depend on the flood condition and physical setting of the delta.

The physical setting of the delta (intervened or natural) also dictates the sediment retained on the delta surface, which varies from 23 MT to 107 MT (6% to 9% of the corresponding sediment inflows) spreading over a sedimentation area that varies from 1922 km^2 to 3720 km^2 (30% to 31% of the corresponding intervened state) depending on the flood condition. As mentioned before, all the high-end values in the parameter ranges of Table 2 represent the extreme flood condition. It is unlikely that such a low probability extreme event (with 200 years return period) would be considered in any sediment management plan because the severity of the flood would be unacceptable to society. However, as these high-end values are also associated with the natural state of the delta, the physical state of the delta plays an important role in determining the most appropriate sediment management plan. It is important to note that in the natural state of the delta a greater amount of sediment is retained within the extended area, which is essential to ensure delta building processes in a uniform way.

Table 2: *Ranges of total sediment input, sedimentation area, retained sediment and sedimentation thickness on the inundated delta surface based on the numerical experiments. The entire coast is divided into three estuarine systems – Western Estuarine System (WES), Central Estuarine System (CES), and Eastern Estuarine System (EES). Sediment input and sediment retained on the floodplains are expressed as annual average values in Million Tonnes (MT).*

Annual Average Values		Entire Coast	WES	CES	EES
Total sediment input (MT)		400 to 1200			
Sediment retained on the floodplains (MT)		90 to 600	45 to 260	30 to 340	17 to 25
Percentage of total sediment input retained		22% to 50%	11% to 21%	8% to 28%	2% to 4%
Average sedimentation thickness (mm)		5.5 to 7.5			
Change from intervened to natural state	Increase of retained sediment (MT)	23 to 107 (6% to 9% increase)			
	Increase of sedimentation area (km^2)	1922 km^2 to 3720 km^2 (30% to 31% increase)			

4. Discussion

4.1 Impacts of Polders on Coastal Flooding and Sedimentation

Our numerical experiments demonstrate that sedimentation thickness on the delta surface depends on the inflow sediment volume, and the retained sediment fraction on the floodplains. Within the same physical settings, the incoming flow and sediment flux during extreme floods is much higher than the flow and sediment flux during the average flood. During both the average and extreme flood conditions in the intervened state, the numerical experiments successfully simulate the prototype observations as sedimentation is mainly confined to the unprotected areas outside the polders. This results in an uneven land building process, which is one of the main reasons for waterlogging inside the polders. However, the observed phenomenon did not happen overnight as the poldered embankments were implemented gradually over a period of three decades. The timing of the water-logged area has been compared with the corresponding poldered area in recent research (Noor, 2018). The study revealed that around 30% of the study area was poldered by the 1970s, increasing gradually to around 60% by the 1990s. Meanwhile, the water-logged area increased from 2% to 5% during the period mentioned above. Since then, the water-logged area increased to around 35% by the year 2016. In addition to the impacts of polders as mentioned above, one of the reasons for the sharp increase of water-logged area within a comparatively short time is inappropriate design and/or poor maintenance of the drainage facilities inside polders.

In contrast, in the natural state, the same volume of floodwater and sediments that enter the region are dispersed over a larger area with more uniform sedimentation. These findings highlight the potential benefits of restoration of quasi-natural conditions to develop sustainable sediment management in the coastal systems of the GBM delta (Wilson et al., 2017; WARPO and BUET, 2020; WARPO and BUET, 2021), especially in the WES (Table 2) which currently has a high density of poldered embankments and suffers waterlogging driven by uneven sedimentation.

4.2 Potential for Enhancing Sediment Retention on Delta Surface

The natural delta state retains sediment on the delta surface in relatively uniform fashion. Depending on the flood condition and intervened state of the delta, the percentage of retained sediments varies from 22% to 50%, with a sedimentation thickness of 5.5 mm/yr to 7.5 mm/yr (Table 2). Therefore, for any flood condition and for any physical state of the delta, the model-simulated sedimentation thickness exceeds the synthesized value of RSLR in this study (5 mm/yr) and the average sediment supply is sufficient to maintain the relative elevation. However, if the sediment supply increases, sedimentation rates would have the potential to further exceed RSLR and create new elevated areas in the delta.

However, to materialize the inherent opportunities (such as land reclamation) and counter different challenges (such as siltation in navigational routes, and salinity-flooding-water logging in cultivable lands), various interventions are being practiced in the coastal zone that can generate unwanted consequences even while fulfilling the specific objectives. Broadly, the practiced methods can be divided into two categories: (i) management to accelerate siltation and (ii) management to promote de-siltation. In the first category, cross-dams and tidal river management (TRM) are usually implemented for land reclamation and to elevate land, while in the second category dredging often complements the use of bandal-like structures that are adopted for the maintenance of navigational channels and landing ports. However, the history, working principles and functionalities for each of the methods are different and these techniques are typically applied in isolation to achieve the goals of the specific projects. Some examples of cross-dams, TRM and bandal-like structures are shown in Figure 6 and discussed briefly below:

Cross-dams are closure structures employed to increase the residence time of marine sediment to enhance sedimentation and are often used for land reclamation between the mainland and islands (World Bank, 2012; Paul and Rashid, 2017). Several implementations of such structures have been undertaken by the BWDB (personal communication) and have achieved successful land reclamation. Examples include the Noakhali Cross-dam 1 in 1957, the Noakhali Cross-dam 2 in 1964, followed by the Muhuri closure dam in 1985, that together have created more than 1000 km^2 of land. Following the success of these projects, a further 19 cross-dam priority sites have been identified by BWDB with the objective of accelerating the natural processes of land accretion. For example, 4 km^2 of new land has been reclaimed by the construction of Char Montaz-Char Khalifa (known as Bestin Closure) in 2009-2010, while the Char Islam-Char Montaz cross-dam was constructed in 2014-2015 and reclaimed 2 km^2 land. More recently, in 2015, a cross-dam was constructed at the estuary of Sandwip Channel over Little Feni river and 3 km^2 of land has been created downstream. However, these advantages are accompanied by inherent drawbacks, such as high instability and potential for continuous change and variability that creates new challenges elsewhere under the altered flow-sediment regime; this affects the existing hydrological conditions and need to be addressed carefully in such as dynamic system (World Bank, 2012; WARPO and BUET, 2020). While cross-dams cause local sedimentation, it is important to note that at the delta-scale there is no net gain in land accretion – rather cross-dams redistribute sedimentation at the delta scale (Angamuthu et al., 2018).

To assess the potential impact of several cross-dams proposed by BWDB, a recent study (WARPO and BUET, 2021) examined the system impacts of these cross-dams by applying process-based numerical model in GBM delta. The study found that these cross-dams, if implemented simultaneously in isolation with other sediment management practices (for example TRM or dredging), changes the tidal hydrodynamics of the GBM systems which may result a long term morphodynamic impact. As most of these cross-dams are planned within the zone of turbidity maximum (EES region), trapped sediments due to these cross-dams cause less sediments to be supplied in the western estuary systems (WES region) and lead to riverbed erosion in this region. At the same time, the increased sedimentation in the cross-dam locations decreases the channel conveyance and cause additional flooding in the regions impacted by cross-dams. The study also found that due to additional retained sediment by these cross-dams, the resulting sedimentation thickness in south-central region (CES) is reduced. The impact of this decreased sedimentation thickness plays a significant role on delta sustainability when compared in Table 2. As we mentioned before, cross-dam and similar sediment management practices although can fulfill the local objectives but may prove to produce unwanted impacts in other regions of the delta.

As discussed earlier with reference to the previous studies, and as further confirmed in the numerical experiments undertaken here, the poldered embankments have de-coupled the floodplains from the peripheral rivers, preventing sediment flow into the poldered areas and ultimately creating elevation differences between the inside and outside of polders; such elevation differences driving waterlogging inside polders.

Tidal River Management (**TRM)** has been practiced since the 1990s to get relief from such waterlogging. TRM involves the periodic cutting and closing of polder embankments at strategic locations to increase the residence time of the sediment rich tidal flow volume and hence accelerate land accretion (or reclamation) inside low lying poldered areas (locally known as *beel*s). TRM also acts to naturally dredge the river which is connected to the TRM system (river-polder-connecting channel-*beel*). However, to solve the problem in a sustainable way in the long-run, such operations are to be shifted dynamically in different low-lying areas which needs prior socio-technical analysis (Rocky et al., 2020).

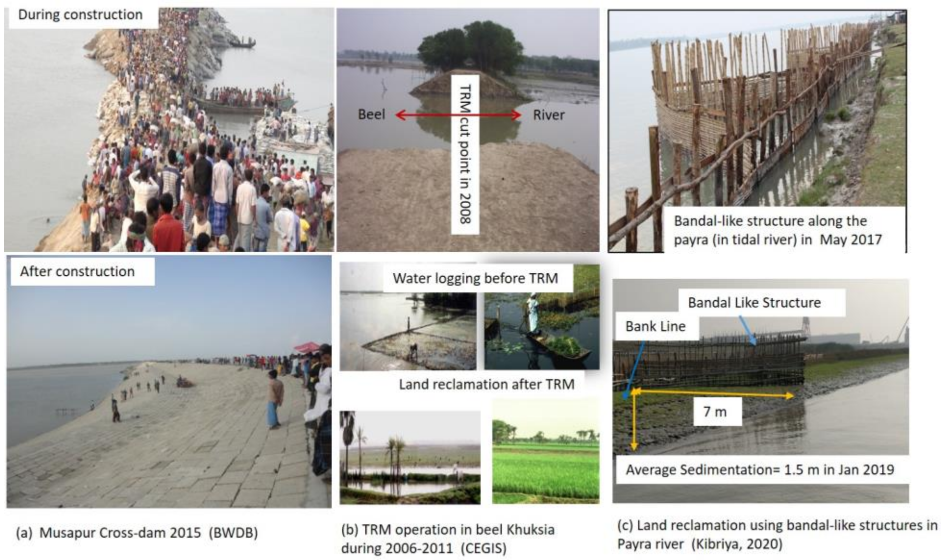

Figure 6: *Field examples of cross-dam (left), TRM (middle) and bandal-like structures (right) as practiced in Bangladesh's coastal zone. Cross-dams are a labor-intensive construction as it needs to utilize the specific tidal phase to construct the main barrier (left-top photo) and later transforms into a permanent structure (left-bottom photo). For TRM, the man-made canal connects the river with the beel (middle-top photo). Due to TRM operation, the natural dredging of the river solves the waterlogging problem (middle-mid photo) and at the same time, fills the beel with sediments causing building of new land (middle-bottom photo). Bandal-like structures are made with eco-friendly soft materials (right-top photo) to stabilize the riverbank with reclaimed land and increase the conveyance capacity of the river (right-bottom photo).*

Bandal-like Structures are indigenous nature-based solution that are primarily utilized for de-siltation along navigational channels, through redistributing the flow-sediment regime to create a sediment deficit zone (within the navigational channels) and a sediment surplus zone (along the bankside). To utilize the power of the flow-sediment regime in bi-directional tidal environments, the shape of the structure is typically modified from a single to double limb (Rahman et al., 2020; Kibriya, 2020) with appropriate opening and inclination that can be utilized for the maintenance of navigational channels and bank stabilization, simultaneously.

River dredging is widely used in Bangladesh for the maintenance of navigational depths in rivers and ports, reduce inundation, and has recently been applied to solve waterlogging problems within polders. However, the impact of dredging is very temporary (WARPO and BUET, 2020). And being costly, the sustainability of dredging is questionable when a long-term morphological time scale is considered. As the riverine and estuarine systems of the delta are interconnected, it is not unlikely that dredging in a specific river/estuary has the potential to change the flow-sediment equilibrium of the system and may change zones of sedimentation on the delta surface, as observed in the numerical experiments undertaken here.

From the above examples, both cross-dams and TRM are implemented to accelerate sedimentation, bandal-like structures are employed to accelerate both siltation and de-siltation, and dredging is employed to increase navigational depth, reduce inundation, and solve waterlogging problem. Such ad-hoc measures that are geared primarily towards solving local problems may contribute to further uneven distribution of delta development processes (Wilson and Goodbred, 2015) and may cause long-term morphodynamic change in the delta (WARPO and BUET, 2021). Moreover, it is not possible to return back to the delta's natural state because the infrastructures are now an essential component to the local people in protecting their land from flooding and salinity intrusion (Rahman et al., 2021). The technical insights of the locally adaptive indigenous methods have already been clarified through a number of research projects (Hussain et al., 2018; Adnan et al., 2020; Rahman et al., 2004; Zhang et al., 2010; Kibriya, 2020) and some of the above methods (Figure 6) have been tested for sediment management purposes in the south-west region of Bangladesh in isolation and have shown mixed experiences of failures/successes with emerging socio-technical challenges (Hussain et al., 2018; Adnan et al., 2020). For any specific sediment management practice or combination of different practices, local impacts often extend outside the domains under investigation and the entire system needs to be considered in an integrated way using a single modelling framework with continuous feedback of data (Bangladesh Delta Model, WARPO and BUET, 2020; WARPO and BUET, 2021) to enable understanding of the system response to the implemented options.

4.3 Potential to Increase Basin Scale Incoming Sediment Flux

It has been shown that sediment input to the GBM system is still sufficient to counterbalance the present rate of RSLR and more, hence there is currently potential for the development of additional land mass in the delta system. However, the observed and expected decline of total incoming sediment load (Rahman et al, 2018; Duun et al, 2018; Dunn et al., 2019), as well as the acceleration of climate-induced sea-level rise (IPCC, 2021), reduce the future potential to counterbalance land submergence in the coastal region of Bangladesh. Moreover, for the strongest mitigation scenario in AR6 the median climate-induced sea-level rise is about 50 cm over the remaining 80 years of this century, that is about 6 mm/yr and RSLR in Bangladesh might increase to 8 mm/yr. Maintaining elevation will therefore require a lot more sediment. Comparatively, based on long term data measured by BWDB, the estimated recent sediment load is found to have been lowered by almost 50% below the average value usually expected in Bangladesh (1 billion tonnes) and is further decreasing at a rate of 10 MT/year (Rahman et al., 2018). However, considering a range of scenarios of climate change (that are typically likely to produce more sediment load) and anthropogenic interventions (which are likely to intercept more sediment thus produce less sediment load), future sediment fluxes are projected to decrease at a slower rate of around 5 MT/year (Dunn et al., 2018). Therefore, it can be assumed that the sediment supply in the GBM system is likely to decline and the potential for offsetting RSLR will also decline over time. Moreover, with a reduced sediment supply to the system, the rivers and coasts will likely experience new challenges related to fresh land loss.

Furthermore, it has long been observed that a large number of basin-scale water diversion structures have already been implemented to meet the needs for socio-economic development in each of the countries sharing the rivers within the GBM systems (Grumbine and Pandit, 2013; Dunn et al, 2018). The primary objective of such water diversion structures is to withdraw water from the main flow and divert it to water deficit regions, but a side-effect of these structures is that they intercept incoming sediment flows (Foufoula, 2013). The conventional head control structures for water and sediment flows over the diversion structures can be revised through introducing nature-friendly technology, for example Piano Key Weirs (PKW) over which sediments can be lifted by turbulence to reduce sediment interception (Machiels et al., 2010; Abhash and Pandey, 2021). Likewise, more innovative basic research is required to adopt appropriate head control elements over the existing and upcoming water control infrastructure. The recently developed system level modelling framework, the Bangladesh Delta Model (BDM), which integrates the entire processes of ocean, coast, Sundarbans, polders, canal network, estuaries, inland rivers of different scales, embankments, wetlands, beels and haors of the Bangladesh delta can be an important vehicle to test potential sediment management options (WARPO and BUET, 2020; WARPO and BUET, 2021) and has further potential to be integrated with existing hydrological models, such as BDWRM (Salehin et al., 2011) that use gridded rainfall data in GBM basins. BDWRM is a hydrological model, but it has the potential to incorporate the sediment flow over prescribed head control structures. The recent understanding of the common threats and possible solutions could facilitate the engagement of policymakers to create opportunities for co-learning to resolve the problems of the shared GBM delta in Bangladesh and India through joint research (Das et al., 2021; Rahman et al, 2020).

4.4 Wider Implications to the Coastal Zone of the GBM Delta

The coastal zone of the GBM delta is one of six hotspots subject to several hazards including unwanted sedimentation and erosion (BDP 2100, 2018). Many infrastructural projects are planned to be implemented across the course of this century, including ports, economic zones, power plants, and tourist spots, and as part of national development and adaptation against climate change (MoEF, 2009; NAPA 2009) new landmass is a pre-requisite for these developments. The results of this present study indicate that incoming sedimentation thicknesses do have potential to maintain the delta elevation above the RSLR, albeit with varying potential in each of the regions. To maximize the sustainable use of these natural resources, identification of different development project sites should consider the trade-off between the natural potential of sedimentation and the development need of the country. The sediment quality is another issue to consider, for example the western system (the Sundarbans) receives marine sediment which re-enters into the system from upstream rivers by traveling through the saline sea, so these sediments are predominantly saline. On the other hand, the central and eastern systems receive freshwater riverine sediments from the Lower Meghna systems. As a result, the ecosystem productivity, livelihood adaptations, and development opportunities in the western system are different from the central and eastern systems.

Commented [DF(1]: What does this mean?

However, most of the development projects in the delta do not take into account this vital information and therefore the knowledge generated in the present research will add value to the Bangladesh Delta Plan 2100 for the effective implementation of future projects. A national strategy for sediment management needs to be introduced in the BDP 2100 based on the latest research on the GBM delta, including lessons learned from other deltas such as the Mekong Delta in Vietnam (Dunn and Minderhoud, 2022). In addition, uncertainties of the future projections of SLR, precise estimates of spatially distributed subsidence, and consideration of the entire GBM in a seamless modeling framework are to be explored in upcoming research.

5. Conclusions

The question of whether sedimentation on the surface of the GBM delta in Bangladesh can maintain its elevation relative to sea level is answered quantitatively in this paper using a calibrated and validated two-dimensional numerical model, developed using the Delft3D modelling platform. Large scale numerical experiments are performed by using average and extreme flood conditions combined with the natural and the existing intervened states of the delta. The main conclusions are:

- In the intervened state, sedimentation only occurs in the unprotected regions (outside the polders), while in the natural state the floodwater and sediments are dispersed and re-distributed over a larger area (~ 30% larger) resulting in relatively more uniform sedimentation.
- The total annual volume of retained sediment on the delta surface varies between 22% and 50% of the incoming sediment input between the intervened and natural states and average to extreme flood

conditions. As a result, average sedimentation on the delta surface exceeds the present value of RSLR (~5 mm/year) in all cases. Sedimentation is lower and shows more variability across the delta in the intervened state.

- Sedimentation can be enhanced by promoting a quasi-natural state. This can be achieved by controlled management of the flow-sediment regime using measures such as tidal river management (TRM), cross-dams, dredging, and bandal-like structures. This would capture more sediment and establish more uniform distribution of sedimentation inside and outside of the polders. Implementing such measures through monitoring the responses, preferably, using a system level model developed, has the potential to promote sediment management in the GBM delta and hence its physical sustainability in the long time.

The methodology developed in this study can be replicated in other similar deltas to analyze the physical sustainability of these vulnerable environments under variable sediment and flood regimes.

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