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The Impact of Embankments on the Geomorphic and Ecological Evolution of the Deltaic Landscape of the Indo-Bangladesh Sundarbans

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Abstract

The deltaic landscape of the Ganga-Brahmaputra delta has evolved through a complex interplay of geomorphic processes and tidal dynamics coupled with the anthropogenic modifications brought over in course of the reclamation of the islands since the late 18th century. The reclamation process was characterized by clearing lands for paddy farms and fish ponds by building a mesh of earthen embankments along creek banks to restrict saltwater intrusion. The length of the embankments in the Indian Sundarbans alone is 3638 km (World Bank, 2014) which altered the tidal inundation regimes, sediment accretion and geomorphic character of the deltaic inlets. The mean annual sedimentation rate (2.3 cm y^{-1}) in the central Ganga-Brahmaputra delta is over two times higher than sedimentation within the natural intertidal setting of the Sundarbans (Rogers et al., 2017). The tidal range has also increased inland due to polder construction, with high water levels within the polder zone increasing as much as 1.7 cm y^{-1} (Pethick and Orford, 2013). Embankments have impacted on the biodiversity and physiological adaptations of mangroves within the sphere of tidal ingression, habitat fragmentation and seedling establishment. The chapter attempts to reappraise the impact of dykes on the geomorphology of the deltaic landscape and on the functionalities of mangrove forests.

Keywords: land reclamation, embankment, tidal dynamics, geomorphology, mangroves, biodiversity

1. Introduction

Tidal energy influences deltaic components, regulates morphodynamic processes and facilitates onshore sedimentation worldwide [1–3]. Regular inundation of the intertidal terrain sustains the Ganga-Brahmaputra (G-B) deltaic plain. Since

the pre-colonial era, the unified G-B delta region in both India and Bangladesh, witnessed construction of earthen embankments along the tidal channels, rivers, coastal stretches and also within the deltaic plain to prevent flooding, salinity intrusion and land erosion [4, 5]. Referred to by the Dutch term ‘polder’, there are low-lying floodplain tracts which are enclosed by the dykes and used for rice cultivation and aquaculture in Bangladesh [2]. These partly-engineered structures not only restrain standard range of tidal flooding but also seize large areas of formerly intertidal landscape. Over the years, the entangled network of rivers fuelling life to the vast stretch of mangrove forests in both India and Bangladesh Sundarbans, has been reduced and the fresh water discharge has been deterred since the rivers got disconnected due to upstream interferences like large barrage and dam installations [5, 6]. In addition, more complex human interventions due to increased population, irrigation, economic activities in terms of flow of goods and requirement for maintaining larger scale infrastructure have magnified the fragilities of the delta over time. For past centuries, a number of embankments have been built in the southwestern side (the Indian Sundarban) totaling to about 3638 km in length [6, 7]. In Bangladesh Sundarban, emerging, more than 129 polders have been constructed in the upstream areas encompassing 13,000 km² of land or, about 44 percent of the total area in deltaic Bangladesh [6, 8].

Several researches in past few years have documented substantial lowering of coastal tracts indicating greater risk of submergence by sea-level rise and amplified inundation by storm surges [2, 7, 9]. This elevation loss is attributed to the sedimentation within embanked channels conjoined with sediment compaction within intertidal platform and removal of forest biomass [2, 9]. Middlekoop *et al.* [10] found an identical condition in their study on Rhine delta where the sediment trapping efficiency of the floodplains is low and largely governed by rivers and engineering works [10]. Again, Hoa *et al.* [11] suggest that the engineering structures in the delta raise the flow velocities in the rivers and canals, increase bank erosion, and cause the water to be deeper in the rivers and canals. This induces flooding in the non-protected areas of the delta and invites the risk of catastrophic failure of the dykes in the protected areas [11]. In this backdrop, this chapter aims to build an understanding on the influences of embankments on the major morphodynamic processes and ecological robustness of the deltaic landscape by appraising and synthesizing a large amount of published data. Artificial barriers the embankments mark abrupt changes in the deltaic landscape and truncate the habitat connectivity. Thus, the specific objectives of the chapter are to (1) document impacts of the embankments and polders on sediment accretion dynamics within different hydro-geomorphic set up of the G-B delta, (2) ascertain the imperatives of seasonal behavior on sediment accretion-erosion processes, (3) appraise the ramifications of embankments on the functionalities of the ecosystem and (4) discuss wider management implications.

2. Study area

Created by the confluence of the Ganges, Meghna and Brahmaputra rivers and their myriad distributaries, the Sundarbans constitutes the southern end of the Ganga- Brahmaputra delta in Bangladesh and West Bengal (India). The geographically undivided Sundarban tract (**Figure 1**) stretches approximately 260 km. west-east along the Bay of Bengal from the Hugli River estuary at the western segment in India to the Meghna River at the east in Bangladesh. Situated at the littoral fringe of the world’s largest deltaic landscape and shrouded by magnificent

Figure 1.
 The integrated indo-Bangladesh Sundarbans. Image details: True color image, (Landsat TM, 1992).

thicket of mangroves, the Sundarbans has a total area of roughly 10,200 km², about 60 percent of which is in Bangladesh and 40 percent in India [6]. This intertidal region receives saline influx from the Bay of Bengal twice a day, whilst is also bathed with freshwater flow from the Ganga-Brahmaputra-Meghna River System [12]. Constituted by total 102 islands, the Sundarbans Biosphere Reserve (SBR) in India is bordered by 54 inhabited islands to the north with a repugnantly contrasting human-modified landscape and the rest are within the mangrove Reserve Forest area. In Bangladesh the mangroves are sheltered in the Sundarbans Reserve Forest which is starkly surrounded by polders, shrimp farms and settlement to the north.

Constructed primarily by fluvial processes, the delta is now maintained almost exclusively by tidal actions and contributed by acute water-surface gradients along the interconnecting tidal channels. The major fluvial systems has either disjoined or migrated to the east and eliminated the most direct fluvial input at the Indian section of the delta due to the Farakka barrage or the Ganges Treaty which was operationalized between India and Bangladesh in 1975. Inevitably, it decreased the perennial flow by diverting a maximum 1133 cumec of water through the feeder canal through Bhagirathi-Hugli river system of West Bengal (India) [6]. Due to this upstream diversion, the distributaries of the Bhagirathi-Hugli have either been disconnected by siltation or dried. Presently freshwater in the rivers contributing to Sundarbans is negligible or mostly absent except during monsoon months [6]. In eastern section (Bangladesh) Gorai-Modhumoti-Passur river systems still contribute substantially unlike the Mathabhangha-Kapotaksha-Sibsa river system which once was significant but deteriorated subsequently.

Coupled with this severe shortage in fresh water discharge from upstream, especially at the Bengal section, incessant embanking at the downstream water courses has notably affected the salinity regimes in the rivers and creeks of the lower section of the delta including Sundarbans. The lower-gradient fluvio-tidal section in the south-east (Bangladesh) is advancing into the sea with comparatively steady-state channels contrary to the fluvially discarded tidal section in the south-west (India) which is accreting vertically but also declining irreversibly in certain sections [6, 13]. However, periodic flooding of the land surface during the tidal cycle coupled with enormous sediment delivery during the monsoon (wet season) promotes sediment accumulation

and heterogeneous surface elevation gain through time [9, 14]. Sediment transport is landward and to the south-west in the Bengal section (India) [13]. Indeed, the flood defensive structures have terminated the pathways of sediment conveyance and inland sediment transport for much of the lower delta region, especially at the south-west section. Thriving at the southern end of the G-B delta and constituting about 47 percent of the deltaic coastline, the Sundarbans as a complex socio-ecological system with i) extended fluvio-deltaic plains, ii) agriculture and shrimp farming and iii) tide-dominated morphodynamic processes, is the focus area of the chapter.

3. A geo-historical account of embankments in the Sundarbans

At the dawn of colonial period the Sundarbans was sparsely populated teeming with profuse flora and fauna as pointed out by Hunter in an essay published in his book 'A Statistical Account of Bengal' [15]. The East India Company presented an image of the tracts that were not under the government's lease and thus, they conferred tenure and activated their revenue-yielding process through the conversion of inaccessible 'wastelands' into paddy lands as early as 1770s [16, 17]. At this time, they also noticed the dilapidated condition of the hitherto built 'public' embankments or mud bunds which were supposed to be maintained by *zamindars* (feudal landlords) as per the reports from resident Collectors and local offices. To secure the returns from the agricultural fields against the tidal inundation, the erection of mud embankments hastened in tandem with land reclamation by the *zamindars* and simultaneously, a complication arose between the British Government and *zamindars* with respect to embankment maintenance responsibilities. Even as the granting of tenure for reclaimed lands proceeded, private landlords encroached to the forestland in order to extend their landholdings beyond the leased plots by setting up 'private embankments' [18]. More than two decades later, migrants were appointed for clearing the land and constructing embankments. During this time, the British Government used to provide subsidy to the *zamindars* for maintaining embankments, but often the work was neglected. In 1793 Permanent Settlement Act was implemented to regulate property rights over land and it also included, for the first time, the provisions about embankment maintenance [18]. But the responsibility for supervision and maintenance of the embankments was finally handed over to the Embankment Committee in 1803 [18]. Despite the decentralization of embankment management, private participation in maintenance work remained inadequate and subsequently, the maintenance of embankments was recognized as public works in the Bengal Embankment Act of 1873 [18, 19]. The 1857–67 Public Expenditure data on embankment maintenance for the districts of Bengal, reported that embankments in the Sundarbans required high repair expenditures on an average per mile relative to other districts because of the fragilities and hazardous nature of the sites [20].

According to Hunter [15] a major part of reclamation work included in keeping out the lateral flow of saline water and thus, bringing the marsh lands under rice cultivation. In availing this method, all the inlets from the channels were embanked, and smaller channels called *poyans* were excavated around their ends. This embanking was usually done in November, after the river water goes down. When the tide is low, the channels were opened, and the water from the inside drains off; when it is high, the channels were closed [21]. These embankments were major means of communication. Eventually, the islands were joined by filling up intervening water courses and raised permanently above the high water levels. During the

19th century, the process of reclamation was speeded up by building embankments which ultimately, retarded the island formation as the silt accumulation was possible only inside the embanked channels instead of the islands. O' Malley's [22] findings stated that the human habitation was eased by the construction of embankments which kept the salt water out from the stretches of the plains. After the abolition of *zamindari* system in West Bengal (India), Irrigation and Waterways Department (IWD, Govt. of West Bengal) took over the responsibility of managing embankment constructions jointly with the Village Panchayats (village councils) [18]. On the other hand, many islands in Bangladesh witnessed rapid poldering as a part of 1960s and 1970s programs to increase available land for shrimp farming and agriculture [23, 24]. Approximately, 5000 km of polder embankments were built by hand which generated 9000 km² of new farmland, but also eliminated the semi-diurnal exchange of water and sediment between the tidal channels and tidal platform [25, 26]. Now these areas lie 1.0–1.5 m below mean high water level due to sediment deprivation coupled with auto-compaction of sediments within the land [2].

4. Morphodynamic processes of the delta

In almost all shallow and active tide-dominated platforms like the southern part of G-B delta, tidal inlets or creeks play a crucial role in governing local morphodynamic behavior and maintaining equilibrium at the landscape level. The equilibrium is achieved by the dynamic interplays among the landscape components which are materials, processes and forms. When the river influx and tidal forcing, averaged over a seasonal cycle are sufficiently steady, tidal channels can evolve towards near-stable morphology. In high discharge phases during wet seasons sediment export is promoted by high transport capacity of rivers which reduces tidal deformation. In contrast, stunted river discharge as a sequel of dry seasons, advocates flooding and facilitates sediment imports only from the estuarine mouth [14]. Hence, the tidal motion balances the delta morphology at the landscape scale as the sediment import during low flow balances sediment export during maximum flow within a seasonal cycle [14, 27]. In fact, the tidal distributaries or creeks, exhibit lesser migration rates and also, are not easily flooded by the river because of opposing non-linear interactivity between river discharge and the tide [28]. This results in more uniform and balanced distribution of discharge across the channels. Historical satellite imagery from the Sundarban mangrove forest depicts that the tidal-channel network in the region has been quasi stable since the 1970s with <2 percent net change in the length of waterways and meager changes in channel widths. Indeed, morphological equilibrium of the tidal inlets is not only dependent on the freshwater discharge, but also sediment transport coupled with grain size characteristics, tidal prism and tidal asymmetry i.e. high energy short duration flood tides, and low energy long duration ebb tides [29].

The bi-directional flow associated with tidal rise and fall, generating huge volume of water inland with amplitude reaching more than 4–7 m during spring tides, is called tidal prism. As the tidal oscillations conduct sediment from the shelf across the delta plain, up to 120 km towards hinterland the tidal prism retains substantial suspended sediment concentrations [30]. Suspended sediment amount may be estimated by the widely applied form:

$$Q_s = aQ^b \quad (1)$$

where, Q_s represents suspended sediment discharge (kg s^{-1}) and Q indicates water discharge ($\text{m}^3 \text{s}^{-1}$). With the propagation of tidal wave up channel non-linear frictional distortions and relative depths of channel beds induce differences in magnitude and duration between flood and ebb tidal waves, also known as tidal asymmetry [31, 32]. The tidal approach of within G-B delta of south-western section (India) depicts pronounced flood dominance and rising tide turns the estuarine channels into sediment sink. Sediment convergence takes place at the turbidity maximum zone (**Figure 2**) where sediments are trapped by outrushing freshwater discharge and onshore tidal deluge. The sediments typically precipitate as velocities decline at the end of the transport path along the upstream reaches of the tidal channels or on the intertidal mangrove platform and small creeks and the process is further sustained by relatively low flow velocity of the falling tide [30, 35]. This tidal pumping [31] is imperative in facilitating vertical accretion in the plains which receive little or no sediment influx from upstream barring Hugli (India) and Baleshwari river (Bangladesh). Sediment deposition at the Sundarbans mangrove platform is measured up to 96×10^6 tons per year which is 10 percent of the annual sediment content of the Ganga-Brahmaputra-Meghna river system [6].

A unit-scale analysis [2] at 48 stations of deltaic Bangladesh, reports that the annual sediment content of the Ganga-Brahmaputra-Meghna river system ($\sim 1.1 \text{ Gt yr}^{-1}$) is competent to aggrade the entire deltaic system at rates of $> 0.5 \text{ cm yr}^{-1}$, provided there is an effective riparian energy enabling dispersal of sediment to various reaches of the delta and also, substantial tidal exchanges carrying the sediment inland supplementing to vertical accretion of the delta. Through their seasonal investigations Rogers *et al.* [31], Auerbach *et al.* [2] and Hale *et al.* [24] inferred steady rates of deposition that are sustained by the large magnitude conveyance

Figure 2.
(a) Sediment transport pattern within the tide-dominated estuarine landscape, after ozCoasts (<https://ozcoasts.org.au/>) [33], (b) key processes generating turbidity maximum zone, after Alongi [34].

of sediment through the tidal channels or estuaries and ultimately supplied by monsoonal discharge of the main-stem rivers. Clearly, regional suspended sediment concentration begins to increase in August, coincident with a decrease in local salinity, indicating the arrival of the sediment-laden, freshwater plume of the combined Ganga-Brahmaputra-Meghna rivers (**Table 1**). Hence, a strong seasonal signal is apparent in this dynamic setting: surface elevation change is positive during monsoon season (July–August) and often negative in dry seasons. These patterns are further supported by onshore sediment transport in a tidal cycle.

As implied by the studies of Hale *et al.* [24], the net sediment transport in a tidal cycle is typically 106–107 kg, with magnitude varying largely with tidal phase and spring tides generating 1.5 to 3 times greater net transport than during neap tides [24]. Together mean sediment discharge and net sediment transport patterns reflect an overall flood-oriented asymmetry and net onshore transport of sediment by the tidal pumping. Such tidally supported sedimentation yields mean accretion rates of $\sim 1 \text{ cm yr}^{-1}$, with local observations often reaching $3\text{--}5 \text{ cm yr}^{-1}$, which indicate favorable sediment delivery to the unified Sundarbans [2, 24]. Bomer *et al.* [37] utilized an array of surface elevation tables, sediment traps, and groundwater piezometers to provide longitudinal trends of sedimentation and elevation dynamics with respect to local platform elevation and associated hydro-period. They compared two hydro-geomorphic settings of the Sundarbans mangrove forest in Bangladesh: higher elevation stream-bank and lower elevation interior. Seasonal measurements over a time span of five years reported elevation gain in all settings, with highest rates reported from elevated stream-bank zones.

On other hand, Syavitski *et al.* [38] estimated values of variables within the delta systems worldwide to compile an index of vulnerability indicating the degree of natural and anthropogenic co-action. Relative changes between the local land-surface elevation and water levels (ΔRSL) are defined by the rates of sediment accretion (A), eustatic sea-level rise (ΔE), compaction (C), and tectonic subsidence (M), as:

$$\ddot{\text{A}}\text{RSL} = \text{A} - (\Delta\text{E} + \text{C} + \text{M}) \tag{2}$$

Based on the model of Syvitski *et al.* (2009), the G-B delta is among the 33 deltas worldwide with risk to a 50 percent increase in severe flooding over the next century as a result of relative sea-level rise. Also, in the past decade, 85 percent of the deltas experienced severe flooding, resulting in the temporary submergence of $260,000 \text{ km}^2$ [38]. Their study specifically constrained the variables, such as sediment aggradation, compaction and subsidence which contribute to the relative sea-level rise. In the case of the naturally flooded and forested Sundarbans, the mean ΔRSL deterministically approaches $\sim 0.0 \pm 0.3 \text{ cm yr}^{-1}$ (that is, no net

Province	Surface area (km ²)	Storage (10 ⁶ t a ⁻¹)	Percent of total sediment discharge of the Ganga and the Brahmaputra*
Bangladesh	4800	62.4	6.2
India	3000	13–32	1.3–3.2
Total	8000	77.4–96.4	8–10

*Total Ganga–Brahmaputra sediment discharge is estimated as 10^9 t a^{-1} by Milliman and Syvitski [36].

Table 1.
Sediment budget of the Sundarban forests, after Rogers *et al.* [35].

change) because abundant sediment supply and regular tidal inundation compensate for local variation in compaction and subsidence [38]. This net balance reflects the historical pattern of dynamic stability in this landscape where sediment accretion has remained in equilibrium with relative sea-level rise (RSL) rise. In contrast, we calculate a ΔRSL of $\sim 1.3\text{ cm yr}^{-1}$ for the sediment starved polder, plus $\sim 20\text{ cm}$ of lowering from wood extraction. These values account for $85 \pm 35\text{ cm}$ of elevation loss in the 50 years since embankment construction [2].

5. Modifications within the embanked landscape

Reclamation of the landscape (Figure 3) with hard, consolidated embankment causes wave and current deflection from the base of the wall causing basal scouring and subsequent subsidence and overtopping. As the cross-sectional area is reduced due to exclusion of intertidal part by reclamation, sedimentation takes place on the channel bed and thereby, raises its elevation [39]. On the flip side, the interior part of islands remains sediment starved and thus subsides due to compaction and de-watering [40, 41]. This develops a reverse gradient with lower central position. Once flooded, water enters into the island and is unable to drain back to the channels (Figure 4b).

Formerly, widespread sedimentation could be possible in the active stretches as the tidal distributaries tended to migrate or witness landward transgression across the plain for maintaining their position within coastal energy gradient [38]. But unplanned construction of these flood defensive walls have hindered the channel migration process and reduced the capacity of small channels to navigate into the larger one. Estuarine transgression, however, is a two-stage process in which lateral erosion of the seaward margins of salt marshes and upper mudflats is balanced by vertical accretion on their surfaces so that their landward margins frontier forward. But the embankments are standing between these two processes, permitting

Figure 3. Embankments and polders in the indo-Bangladesh Sundarbans [6].

Figure 4.
(a) Typical south-western deltaic landscape with embankment, (b) cross-section of the delta plain: River bed lies above the land behind embankment, (c) post-cyclone ('Amphan', 2020) damages of earthen embankment in Indian Sundarban.

the erosion to take place to seaward preventing the accretion to landward [41]. Moreover, a number of interior creeks and estuaries are exposed to unprecedented siltation, especially at the western part of the lower delta stretch, as a consequence of reduction in tidal spill [42].

Four types of embankments are commonly built at the south-western section of the delta: i) 2 m high earthen wall bordering small tidal channels, ii) 2 m high earthen wall with brick pitching on island margins, iii) 3 m high wall with brick pitching on wave exposed coastal tracts, iv) 3.67 m high wall with boulder pitching on eroding stretches [6]. On other hand the tidal creeks of Sundarbans are classed as meso-macro tidal having amplitude ranging from 2 to 5.5 m. The incoming tidal waves during spring tides and wet months often achieve the height of more than 3 m (often 4 m) to overtop the barrier and thereby, enter into the agricultural lands [40]. Clearly, this positive feedback loop discards the embankments as a protective wall from saline water. Further, deep foundation of embankments impairs the dynamic interconnection between ground water table and river by retarding influent and effluent seepage [43]. The embankment on the bank is affected by the hydrostatic pressure causing uplift and dislodgement of such structures. The scouring of the bank along the concave side of meander and heavy weight of overlying structure often leads to collapse of the banks.

Beginning in the late 1960s and continuing to the early 1980s, ~5000 km² of the low-lying tidal delta plain of Bangladesh section was embanked and converted to densely inhabited, agricultural islands i.e., polders. From this section of Bangladesh Wilson *et al.* estimated the closure of >1000 km of primary creeks due to direct blocking by embankments and sluice gates [13]. This precludes natural exchange of water and sediment that defines the delta plain [44]. Without the regular delivery of sediment to the land surface from tidal overbank flooding over the last 50 years, significant loss in elevation (1–1.5 m) relative to mean high-tide levels has occurred, culminating in enhanced flood risk in the event of embankment failure [45]. Moreover, Polder construction reduced local tidal prism by remaining channels, lowered local current velocities and favored enhanced sediment deposition. Most infilling takes place along one or more channels which have been beheaded from

Figure 5. Standard polder system of the south-eastern section (Bangladesh) of the delta. Siltation within tidal channels result in formation of khas land, but increased waterlogging within depressed polders; modified after Wilson and Goodbred [13].

Year	Poldered Area			Natural Area		
	1973	2003	2013	1973	2003	2013
Length of tidal channels outside of polders (km)	1891	783	782	1964	1987	1981
Length of tidal channels obstructed by polders (km)	0	1108	1108	0	0	0
Length of tidal channels outside of polders with >50% obstruction [<i>khas land</i>] (km)	0	355	420	0	0	0
Change in drainage network			–59%			1%
Conduit channels converted to <i>khas land</i>		45%	54%			0%

Table 2. Summary of results from GIS analysis (1973–2013), after Wilson et al. [13].

the tidal network, reducing their local discharge and permitting sediment deposition. Subsequently, new lands are constructed on the infilled, shallower tidal channels surrounding the compacted, sediment-scarce polders. These are called *khas land* (**Figure 5**) [13]. The northern section of Sundarban Reserve Forest (SRF, Bangladesh) constitutes of the polders and the *khas land* only (**Table 2**).

6. Discussion

6.1 Geomorphic ramifications of dykes

The massive shrinkage in inter-tidal areas by the artificial barriers affected natural ability of the system to respond to and dissipate flood energy. In many parts of the delta, the land behind the barriers is now lower than the inter-tidal areas

or channel beds: an apparent sign that the system dynamics has been disrupted (**Figure 4**). Construction of marginal levees increases channel depth and accentuates flood dominance which further, aggravate sedimentation at the channel bed as the channel tries to restore its equilibrium [46]. The major waterways lose their original widths. Consequently, the 'conduit' channel beds procure substantial elevation by infilling processes as opposed to the land behind the embankments. In the state of morphological equilibrium, length of a resonant macro-tidal estuary like the Hugli (Indian section), tends to equal a quarter of the tidal wavelength (L) [46, 47], i.e. 0.25 L. As explained by Bandyopadhyay (1997), the tidal wavelength (L) is determined by the following equation:

$$L = T\sqrt{gD} \quad (3)$$

Where, T is tidal period (constant in a given locality), g is gravitational acceleration (a constant) and D is mean depth of the estuary (the only variable). Reclamation by restricting the area of tidal spill through marginal embankments increases the mean depth and leaves the estuary out of equilibrium to which it tries to return by active in-channel sedimentation and bank erosion to decrease mean depth [5]. With its length 0.17 (i.e. less than a quarter) of its tidal wavelength, this is the situation of the Hugli estuary [5].

Post-storm (category-I cyclone 'Aila', 2009) investigation of Auerbach *et al.* [2] at five sites of breached embankments in south-eastern section (Bangladesh) of the delta, imparted that four of the five breaching has been occurred at the mouths of former tidal channels which are now blocked by embankments. The storm surge height was only 0.5 m above the usual spring tide level. All the breached sites have witnessed ~50–200 m of bank erosion in the decade before the storm and the beach tidal channels have scoured into fine silt at all the spots. During 2 years before the repair, much of the polder was submerged during each high tide, whilst the adjacent Sundarban, at ~100 cm higher, was inundated only in spring tides. This reflects the sediment scarcity within the polders and historical loss of surface height (**Figure 5**). Auerbach *et al.* [2] reported that the embanked islands in southwest Bangladesh have lost 1.0–1.5 m of elevation, whereas the neighboring Sundarban mangrove forest has remained comparatively stable. Sediment starvation has impacted on tidal inundation pattern by inflating local tidal prism i.e. volume of water moving on and off the polder within the polder. In this case, the substantial loss of elevation has severely exacerbated the effects of tidal inundation by increasing the tidal prism accounting for the exchange of $\sim 62 \times 10^6 \text{ m}^3$ of water through the breaches during each tidal cycle.

On other hand, there has been substantial channel infilling by interlaminated silt and mud in association with reduced tidal prism and current velocities outside polder walls. The combination of these geomorphic responses has led to many channel beds becoming shallower than polder elevations, which exacerbates water-logging in polders [2, 13]. Wilson *et al.* [13] have estimated the blockage of >1000 km of primary creeks in Bangladesh section directly by embankments. Additionally, the infilling of tidal channels outside the polders often disconnect the channels from the tidal network thereby reducing local discharge. Through the field-based experiments they accounted for 60 percent decrease in total length of channels across ~3000 km² poldered area which corresponds to a loss of nearly two thirds of the region's waterways over the past 40 years. Indeed, the infilled water systems of Bangladesh section are altered from navigable tidal channels that proffered public fishing grounds and aquatic habitat, to well-defined land plots that

are, inevitably, reclaimed and typically used for either paddy cultivation or shrimp farming [48, 49].

6.2 Impacts of dykes on ecological evolution

Mangrove swamps, with interspersed tidal channels flanked by the estuary, serve as a depocentre for fine sediment. It is important to note that, interaction between fresh water and saline tidal water at the mineral-rich turbidity maximum zone leads to flocculation or aggregation of clay or silt particles, followed by the settlement of macro-flocs [26, 50]. Diurnal and semi-diurnal tidal deluge deforms significantly inside the mesh of mangrove trees and intertwining roots. As the sediment-laden tidal water enters to the platform, the flow speed is slackened by the dense distribution of aerial roots and further, turbulence is generated by flow around the trees and roots. The turbulence induces eddy formation leading to collision of particles and development of flocs. Here, settling of flocculated sediments takes a shorter time (<30 minutes) during the flood-ebb transition. Settling is also enabled by sticking of microbial mucus and percolation of water through animal burrows on the swamp floor [50]. Hence, sediment trapping on the floor plays a dominant role in building new land and further, sheltering mangrove ecosystem.

Reversing tidal flows complement exchange of materials, such as nutrients, dissolved oxygen, mangrove litter etc. between mangrove areas and coastal waters [36]. In addition, viviparous germination of mangroves in association with unique propagule dispersal and subsequent, seedling establishment processes are supported by the gentle slope of bottom substrate, loose bottom sediments and water inundation into the swamp area and channels during the tidal period. Mangrove propagules have an obligate dispersal phase for several weeks before the radicle extends for root development. The dispersal depends on their buoyancy, longevity and action of tides and currents. After the period of obligate dispersal the healthy propagules anchor at the soft, muddy slope of channel banks and swamps. Mangrove propagules are not only the key to mangrove propagation and regeneration, but also are significant storage potentials to atmospheric carbon [51]. Moreover, species-level zonation and distribution of mangroves are attributable to the dispersal and seedling anchorage patterns. For instance, freshly fallen gray mangrove propagules, such as *Avicennia*, are floated on the flood tide and strand near high water of the ebb; subsequently the pericarp is shed and the newly released seedling does not refloat on the next tide. These attributes describe the tendency of *Avicennia* to find higher densities of seedlings in the upper mangrove zone than in the lower zone [52]. The brick slopes at the forest-fringed island margins hinder the seedling anchorage at the channel banks; thereby the propagules often become unhealthy after refloating several times. Moreover, embankment construction along the tidal channels often leads to felling of mangroves, especially at the south-western section.

The mangrove environment should be understood as a component of the total ecosystem that comprises the river basin, river, and estuarine and coastal waters, forming an ecohydrology system that should be considered holistically [17]. Physical processes within the mangrove swamps of the Sundarbans, especially, processes of water movement, are imperative in maintaining the functional characteristics of the mangrove ecosystem and building new land. Water circulation and the dispersion of material in mangrove swamps control both the aquatic and terrestrial biodiversity and nourish mangrove colonies. Frequency of tidal inundation, volume of tidal prism, duration of flooding at long time scales and salinity gradients determine species-level structural and phenological variability of mangrove forests [36]. But the brick dykes along the water bodies have fragmented the network of

tidal channels and mangrove areas in the lower stretch of the delta, especially at the south-western section. As the embankments disjoin forest-river alliance in the buffer and transition areas of the Sundarban Biosphere Reserve (SBR, India), it inevitably, influence the tidal inundation pattern at the core area forest swamps.

Figure 6.
Representative vegetation profile along a mud bank without embankment [41].

Figure 7.
Embankment structures, surrounding the islands, hinder free dispersal of mangrove propagules and thereby, affect mangrove regeneration in the Indian Sundarban (IRS 1D, LISS-III, 2002).

As mentioned before, inflated tidal prism within the enclosed tidal channel further reduces sediment entrainment towards the forest swamps, instead deposit it on the channel bed giving it a higher elevation. Hence, the swamp elevation gets lowered by sediment deprivation over time which, in turn, affects the zonation pattern of mangroves. Looy *et al.* [53] studied the effect of disruption of alluvial forests from natural river flooding on their vascular plant diversity in the river Meuse floodplain in Belgium. Flooding frequency was the most important for correlation within community composition of the forests. Forests still under influence of the river were significantly richer in species diversity pattern from the stream bank and across in the deltaic Sundarbans. **Figure 6** depicts the ideal vegetation zonation pattern from the stream bank and across in the deltaic Sundarbans. Along-channel artificial armor interrupts the normal hydro-geomorphic set up, disconnects their association to the channels and thereby, affects habitat conditions of the mangroves.

Excavation of burrows or 'bioturbation' by fiddler crabs (genus *Uca*) is an important component in mangrove ecosystem functioning as they influence sediment distribution, quality and composition and also aid in aeration and enrichment of the soil organic matter. Moreover, it influences the functions other soil associated organisms. But, the construction of brick and cemented embankments has threatened the habitat of these tillers [54]. Frequent breaching and overtopping of the dykes lead to salt water ingress and flooding in the low-lying agriculture and aquaculture tracts within the islands affecting the floral community which thrive on fresh water. **Figure 7** depicts the embankment enclosures opposite to the reserve forest region in Indian Sundarban.

7. Management implications

The embanked and poldered landscape is incompetent to withstand the current pace of sea-level rise and storm surges. Even, implementation of management plan is seemingly complicated at the present form of social and political alignments in both the countries. However, there prevails severe lack of researches about environmentally and socially suitable management aspects. Wilson *et al.* [13] asserted for a potential restoration method of many polders by providing sufficient sediment input from the infilled water bodies. Dredging of *khas land* and infilled tidal channels could restore the waterways as well as fulfill the sediment demands of low-lying polders. In some parts of Bangladesh this restoration process has been implemented through the local approach of Tidal River Management; but the output has been mixed with social and engineering challenges. Nevertheless, long term sustainability of the delta plain with respect to embankment and polder tract management could be feasible through integration of both local knowledge and scientific knowledge.

The role of mangroves in protecting coasts against storms and coastal erosion has been widely acknowledged. Sea level rise and tidal hydraulics entanglements often result in erosion of sea-facing islands and estuary margins and thereby curtail the land area progressively. Indeed, conservation and restoration of mangrove forests are crucial in order to protect the island as well as prevent the surge of sediment input inland. At this juncture, planting mangroves on the artificially built sediment terraces alternated by brick blocks on the embankment slopes might occupy some amount of sediment as well as protect the banks. However, Aamir and Sharma [55] have experimented with the novel 'Porcupine system' which regulates flow energy at a definite reach of river, prevents scouring at the bottom river bank and induces sedimentation. A Porcupine is a unit with six bars which are joined by iron nuts and bolts giving it a tetrahedral frame. In real sense, the frame acts as a substitute of a tree in effectuating turbulence generation and resisting sediment entrainment by flow of

water (**Figure 8**). The technique, however, might be applicable in poldered tracts by linking the area with the surrounding tidal channel through a narrow conduit. Once a part of the excessive sediment-laden water is passed to the depressed polder area the porcupine frames on the depressed area could retard the flow energy and facilitate sediment accumulation. Indeed, the height and spacing between the Porcupine frames need to be relative to the amount of incoming water within a tidal cycle.

Already established earthen walls pressurize the soft, compressible riverine soils and the collapsing tendency temporarily brings disastrous impacts on the livelihoods of the region. Geotextile as a state-of-the-art geosynthetic-reinforced structure is considered to be one of the useful and cost-effective environmental applications, especially for embankment management [56, 57]. Geotextiles are flexible and permeable continuous sheets of woven, non-woven or knitted fibers or yarns. Geogrids which are uniformly placed array of apertures between their longitudinal and transverse elements, permit direct contact between soil particles on either side of the sheet. Geocells are relatively thick, three-dimensional networks constructed from strips of polymeric sheet. The strips are conjoined to form

Figure 8. (a) Sediment deposition around porcupine units in river Brahmaputra, (b) three-dimensional sketch of a porcupine unit, after Aamir and Sharma [55].

Figure 9. Different types of geosynthetic methods to control stability and settlement of embankments. (a) Two-layered geotextiles with folded ends, (b) embankment with vertical piles or geogrids and (c) embankment with geocells [56].

Figure 10.

Naturally grown clump of vetiver grass at Kuakata, Bangladesh. Image courtesy: Islam [59].

interconnected cells which are filled with soil and sometimes concrete (**Figure 9**). Geotextile layers intensify the embankment stability by virtue of two primary functions: tensile reinforcement and as a drainage element reducing pore pressures [58].

Apart from the aforementioned methods, plantation of long-rooted vetiver grass (**Figure 10**) (*Vetiveria zizanioides*) is getting exposure in management applications in India and world. Slope stability and river bank protection capability of vetiver grass by rapid draw down, has already been acknowledged by the environmental scientists. Inhabiting in the tropical and subtropical regions, it develops a simple vegetative barrier of rigid, dense and deeply rooted clump grass, which slows runoff and retains sediment on site [59]. Islam [60] studied the performance of *binna* or vetiver grass on 18 coastal polders over 87 kilometers of earthen coastal embankment of Bangladesh during the period from September 2000 to October 2001. His studies inferred to manifold guidelines for applications of vetiver grass coupled with its successful propagation and better performances. This cost-effective bio-engineering method may be applied extensively in the embankment tracts of the Sundarbans in order to provide it an ecological mode of support.

8. Conclusion

Estuarine stretch of the G-B delta plain is considered to be a broad system with nature-wetland subsystem and human-social sub-system being interconnected to one another. Embankment as a product of the human-social processes plays a key role in governing the steady-state of the entire system. The ever escalating population has left this fragile plain densely settled. Furthermore, as livelihood generation and increasing demand for food are two key concerns behind agriculture, the inhabitants of this region perform a consistent task of protecting their lands from being swallowed by saline water. Embankments, in fact, made cultivation in apparent saline soil possible since historical past. The system is, however, disturbed and the functions of different components of the landscape are modified due to the stark separation between the two subsystems. While embankment breaching is seemingly destructive to the land use and livelihoods of the inhabitants, the long-term impacts of these walls by far more dubious to the deltaic physical and ecological processes. This chapter documents here, i) changing tidal inundation pattern and morphodynamic characteristics within the tidal channels or primary creeks due to the artificial structures, ii) shifting of sediment deposition and

channel infilling as contrasted to previously intertidal deltaic plain and iii) gradual alteration to mangrove functionalities and habitat with respect to seedling establishment, swamp flooding and fragmentation. Most of the suspended sediment that is imported landward on flood tides is instead deposited within channels, resulting in the infilling and closure of >600 km of intertidal channels and emergence of ~90 km² of new land in the southwest delta [13]. Current researches as representative of mean annual sedimentation in the central fluvial-tidal G-B delta indicates that the cumulative vertical accretion rate (2.3 cm y⁻¹) is over two times higher than sedimentation within the natural intertidal setting of the Sundarbans [61]. Explicitly, the chapter attempts to reassess the previous studies and searches for feasible and sustainable routes to delimit the degree of nature-society conflicts in this embanked landscape.

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