

Article

Living Shoreline: Preliminary Observations on Nature-Based Solution for Toe-Line Protection of Estuarine Embankments and Mangrove Regeneration

Paromit Chatterjee ¹, Sugata Hazra ¹, Anamitra Anurag Danda ^{1,*}, Punyasloke Bhadury ²,
Punarbasu Chaudhuri ³ and Sampurna Sarkar ¹

¹ Sundarbans Delta Programme, World Wide Fund for Nature-India, 1641 Madurdaha, Kolkata 700107, West Bengal, India; paromit chatterjee@gmail.com (P.C.); sugata.ocean13@gmail.com (S.H.); sampurna.sarkar10@gmail.com (S.S.)

² Centre for Climate and Environmental Studies, Indian Institute of Science Education and Research Kolkata, Mohanpur 741246, West Bengal, India; pbhadury@gmail.com

³ Department of Environmental Science, University of Calcutta, 35, Ballygunge Circular Rd, Kolkata 700019, West Bengal, India; punarbasu_c@yahoo.com

* Correspondence: aadanda@gmail.com

Abstract: Here, we discuss the results of an experiment in toe-line protection of estuarine embankments from frequent slope failure using silt traps. We test the feasibility of terracotta rings to trap silt and promote natural mangrove regeneration in barren patches in front of embankments around human settlements in the Indian Sundarban region, designated as the Sundarban Biosphere Reserve. The initial results of the first sixteen months of observations, between May 2023 and August 2024, are encouraging. Sediment accumulation in the silt traps across sites ranges between 4 and 42 cm. Periodic granulometric analyses of sediments indicate that while the middle estuarine sites accumulate more clay/silt, the lower estuarine sites accumulate more sand. During the late and post-monsoon seasons, all sites except one, on the eastern coast of the lower estuarine island, exhibit natural mangrove regeneration, the main species being *Porteresia coarctata*, *Sueda maritima* and *Avicennia marina*. Additionally, oysters *Saccostrea cuculata* and occasionally *Crassostrea cuttakensis* are found attached to the terracotta silt traps. The results highlight the potential of the nature-based Living Shoreline strategy to support mangrove regeneration and toe-line protection cost-effectively. The study also successfully opens up new possibilities for sustainable elevation management in the sinking and shrinking mangrove region of the Sundarbans, a significant development in the face of climate change and accelerated sea level rise.



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Keywords: toe-line protection; coastal erosion; nature-based solution; Sundarbans; mangrove regeneration; oyster colonization

1. Introduction

The Sundarban Biosphere Reserve (SBR) in India encompasses 48 mangrove forest islands and 35 inhabited islands, the latter being protected by nearly 1800 km long earthen embankments [1]. The embankments are often armored by brick or concrete. Human habitation on such islands generally lies at lower elevations relative to high tide levels, exceeding 5.9 m during August [2].

Erected since the 18th century, the embankments make human settlements in the Sundarbans possible by keeping saline water at bay. During tidal cycles, the toe of the embankments often erodes, leading to slope instability and vertical collapse of the protective

structure. Currently, the embankments are maintained by the West Bengal Irrigation and Waterways Department. About 90% of the embankments in SBR have a crest height of 2.5–3 m, except for the sea-facing embankments with reinforced concrete that have an elevation of up to 5.75 m [3]. High-intensity weather events, like cyclones, often cause major damage to the embankments. For instance, during the cyclonic event Aila, in 2009, approximately 177 km of embankments were washed out or breached and an additional 601 km sustained severe damage [4]. The embankments fail frequently during tidal/storm surges, which can be as high as 7 m [5]. In some areas, damaged embankments have been reconstructed with brick and concrete armor. Such reconstructed structures have effectively prevented flooding during subsequent cyclonic events, such as Amphan in 2020 and Yaas in 2021. However, armored embankments are expensive to construct, costing approximately USD 0.87 million per km, and require 20–25 m of private land on the landward side [4]. In the Sundarbans, acquiring private land is a challenge. SBR has a population of over 4.5 million people and a population density of over 1000 persons per sq. km [6]. Acquisition of marginal landholdings displaces households, impacting their lives and livelihoods.

Coastal erosion is prevalent in the region [7]. Since 2000, the SBR has witnessed a significant increase in net land loss, approximately 550 ha per year, surpassing the rate of about 400 ha per year observed in the preceding decade [8]. The short-term fluctuation in the rate of coastal land loss shows a close correspondence with the interannual variability of the rate of sea level rise [9]. Compared to the neighboring areas, the close correspondence exists despite the impact of storms, subsidence, and decline in sediment supply [10]. All of these phenomena have a bearing on the stability and longevity of the estuarine embankments.

In January 2019, the Indian Ministry of Earth Sciences (MoES) reported that the rate of sea level rise at Diamond Harbour, located at the margin of the SBR, was above 5 mm per year during the period 1948 through 2000, making it the highest in the country [9]. All sea-facing forest islands of the SBR have experienced significant losses in the mangrove forest area. Anthropogenic disturbances, such as curtailing sediment supplies, modifying channels and changing land use, have also led to land loss [11]. Upstream damming, reservoir trapping, and engineering controls across the delta in the late twentieth century have led to a nearly 30% reduction in sediment delivery to the delta [12]. Reduction in sediment delivery can further trigger accelerating coastal erosion [13]. Therefore, reduced sediment supply and rising sea levels are considered the most important driving factors behind land loss in SBR [14].

Toe-line erosion poses significant challenges to estuarine embankments necessitating the construction of hard engineering structures. While initially effective, these hard defenses deteriorate over time and require continuous investment for upkeep [15]. Moreover, hard engineering structures lack adaptability to changing coastal conditions and can result in the loss of vital intertidal zones crucial for the survival and functioning of biodiversity including aquatic flora and fauna [16]. However, nature-based solutions such as Living Shoreline as a line of protection to the existing embankments offer a more sustainable shoreline management option to address erosion and contribute to the preservation, enhancement and restoration of natural habitats [15,17]. The Living Shoreline strategy, with artificial oyster reefs, has been used in Bangladesh [18] and in the United States of America [15,19,20].

In the context of the Indian Sundarbans where areas in front of the embankments are often bereft of vegetation, the Living Shoreline is conceptualized as a vegetative protection for the embankment. The conceptualization is based on scholarly observations that mangroves in front of embankments significantly enhance their durability [21,22].

The objective of the Living Shoreline experiment in SBR is to study the feasibility of the following:

- (a) silt entrapment in terracotta rings, and
- (b) mangrove regeneration in trapped silt.

The hypothesis was that if sediment was retained, it could encourage natural vegetation growth and associated components of mangrove biodiversity, possibly providing toe-line protection to embankments and enhancing their longevity [23,24]. This paper outlines the methodology and initial findings on sediment retention in the Sundarban Biosphere Reserve, utilizing an adapted version of the Living Shoreline strategy.

2. Materials and Methods

2.1. Methodology and Experimental Setup

For the experiment, we utilized terracotta rings as silt traps. Such terracotta rings have been used for lining dug wells and soak pits in India since 500–400 BC [25]. We installed terracotta silt trap structures at seven sites within the SBR: three at the lower estuary and four at the middle estuary (Figure 1), in front of the embankment around inhabited islands, covering a total area of 3684 m² (Table 1). Located in the lower estuary, Sites 1 to 3 are ~15 km away from the estuary mouth, with Sites 1 and 2 positioned on the island's western side and Site 3 on the east. One site (Site 4) is at the sheltered middle estuary (~60 km from the estuary mouth) on the southwestern side of the island. Three other sites (Sites 5 and 6 on the western side of the island and Site 7 on the east) are farther north and east in the middle estuary (~73 km from the estuary mouth) (Figure 1). The terracotta silt trap installations were carried out in places without vegetation and followed a similar design. The installations in the SBR commenced in June 2022 and continued till February 2023.

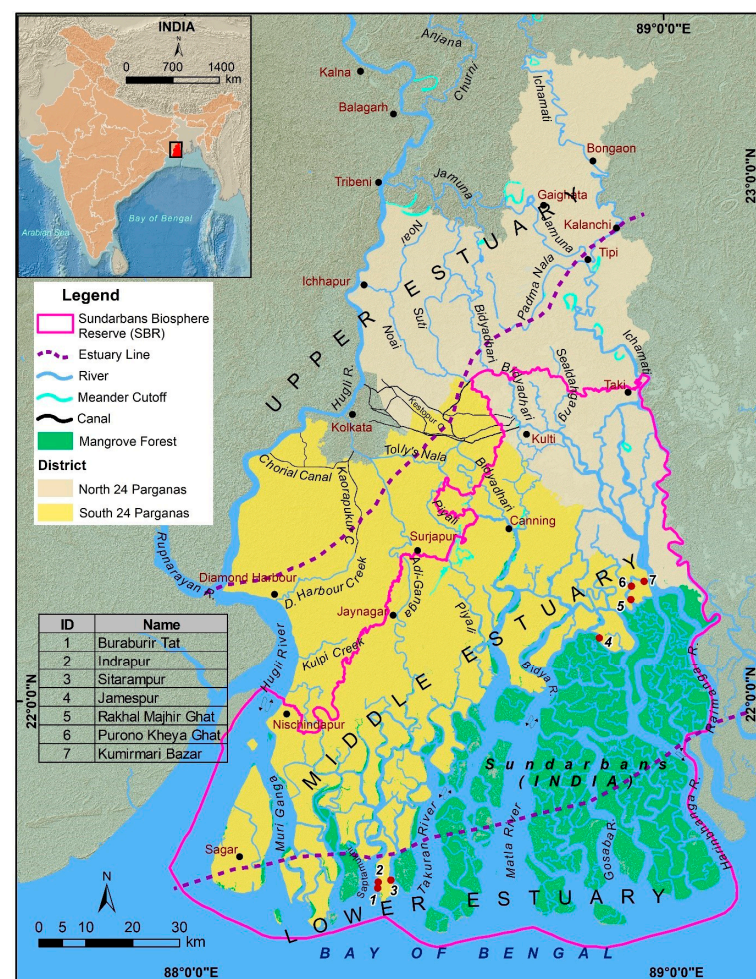


Figure 1. Silt trap installation sites in the Sundarban Biosphere Reserve.

Table 1. Details of the silt trap installation sites in SBR.

Site ID	Site Name and Time of Installation	Lat	Long	Distance from Sea (km)	Aspect	Area (m ²)
1	Buraburir Tat: June 2022	21.63476	88.38607	15.38	N-S (170°)	600
2	Indrapur: November 2022	21.64649	88.38712	16.5	N-S (190°)	600
3	Sitarampur: December 2022	21.64978	88.41336	16.8	NW-SE (140°)	600
4	Jamespur: September 2022	22.11456	88.84981	62.66	N-S (175°)	727
5	Rakhal Majhir Ghat: January 2023	22.18778	88.91619	69.45	NW-SE (145°)	577
6	Purono Kheya Ghat: February 2023	22.21382	88.91765	72.33	N-S (170°)	477
7	Kumirmari Bazar: February 2023	22.22277	88.94387	73.1	E-W (260°)	103

2.2. Intervention Design

Silt traps of three different sizes were procured, as per market availability, and installed for this experiment. Silt traps or terracotta rings of 23 cm in height and diameters of 92 cm, 79 cm, and 61 cm, respectively, were installed along the bank slope in front of the embankments. The angular difference between the first row and the last low of structure for each structure was approximately 2° or ~25 cm, mimicking the bank slope in front of the embankment. A series of single-tier smallest-diameter silt traps were installed on the waterside, followed by four rows of medium-diameter silt traps, and three rows of larger-diameter silt traps on the landward side. The last row on the landward side consisted of two-tiered smallest silt traps (Figure 2). Every installation was 6.5 m wide.

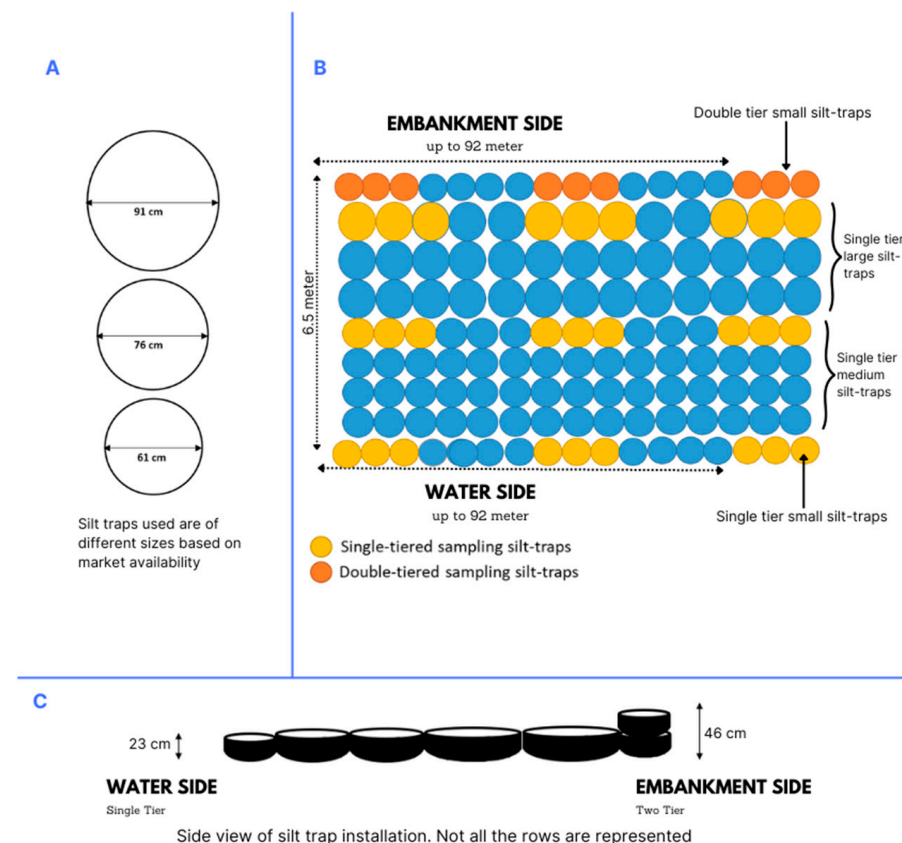


Figure 2. Silt trap installation design, along with marked silt traps for monthly sediment sampling. (A) Represents the different sizes of the terracotta silt traps used in the study; (B) represents the silt trap installation design; and (C) represents the side view of the design.

2.3. Monitoring of Sediment Deposition

Installed silt traps were monitored monthly to check for sediment deposition and the emergence of natural vegetation and oysters within and around the silt traps. Sediment measurements were taken on the day of the highest high tide of every month. At the time of installation, a tin sheet was placed at the base of the silt traps to be monitored. A typical steel measurement ruler (61 cm) was used to measure the sediment deposition (thickness). The ruler was inserted until it touched the tin sheet at the bottom. Since the installations were carried out at different times, the data used for this article are for a common observation period between May 2023 and August 2024. For each site, net sediment accumulation was calculated as retention after 12 months. We subtracted the initial sediment deposition height, measured at the commencement of the study period (Month 1), from the final deposition height recorded in August 2024. Following Chauhan et al., 2014 [26], the granulometric analysis of sediment was conducted to ascertain the proportion of sand, silt, and clay. Sediment samples were collected from within identified terracotta rings, adjoining barren area, and the vegetated area closest to the experimental site to check if the proportion of sand, silt, and clay was any different within and outside silt traps.

3. Results

Natural growth of the mangrove saplings was observed across each site. No mangroves were planted in the terracotta rings. Oysters were found colonizing the terracotta rings.

During the study period, at Sagar, the Monthly Mean High Tide Level (MMHTL) was 474 cm, while the Mean Monthly Low Tide Level (MMLTL) was 145 cm. The highest high tide was 599 cm and the lowest low tide was 26 cm [2,27]. Sediment accumulation was highest outside the monsoon period when the relative water levels were low. Peak sedimentation was observed in February, coinciding with the lowest low tide period. Conversely, sediment removal took place most notably during the high-water levels of the monsoon months, with the highest removal occurring during the highest high tide period. Sediment removal began around the time of the spring equinoctial tide at the end of March. Sediment accumulation resumed following the autumn equinox in late September.

In the lower estuary, Sites 1 and 2 exhibited notable variability in sediment thickness, with peaks occurring during the pre-monsoon (Site 2) and post-monsoon (Site 1) months (Figure 3, top plate). Sediment thickness at Site 3 rose to around 25 cm during pre-monsoon and sediment removal started with rising water level (high tide). Site 3, on the eastern coast (Table 2), showed a phase lag of over a month in accumulation and removal pattern relative to Sites 1 and 2, on the western coast. Sediment thickness at the sheltered middle estuary (Site 4) was the least impacted by seasonal tidal fluctuations (Figure 3, middle plate). The sediment thickness was on average 22 cm. The easternmost sites (Sites 5–7) showed the highest sediment thickness levels (Figure 3, bottom plate), with significant seasonal fluctuations. Site 7, on the eastern coast, sheltered from the thrust of the flood tide, recorded an average sediment thickness of around 32 cm (Table 2).

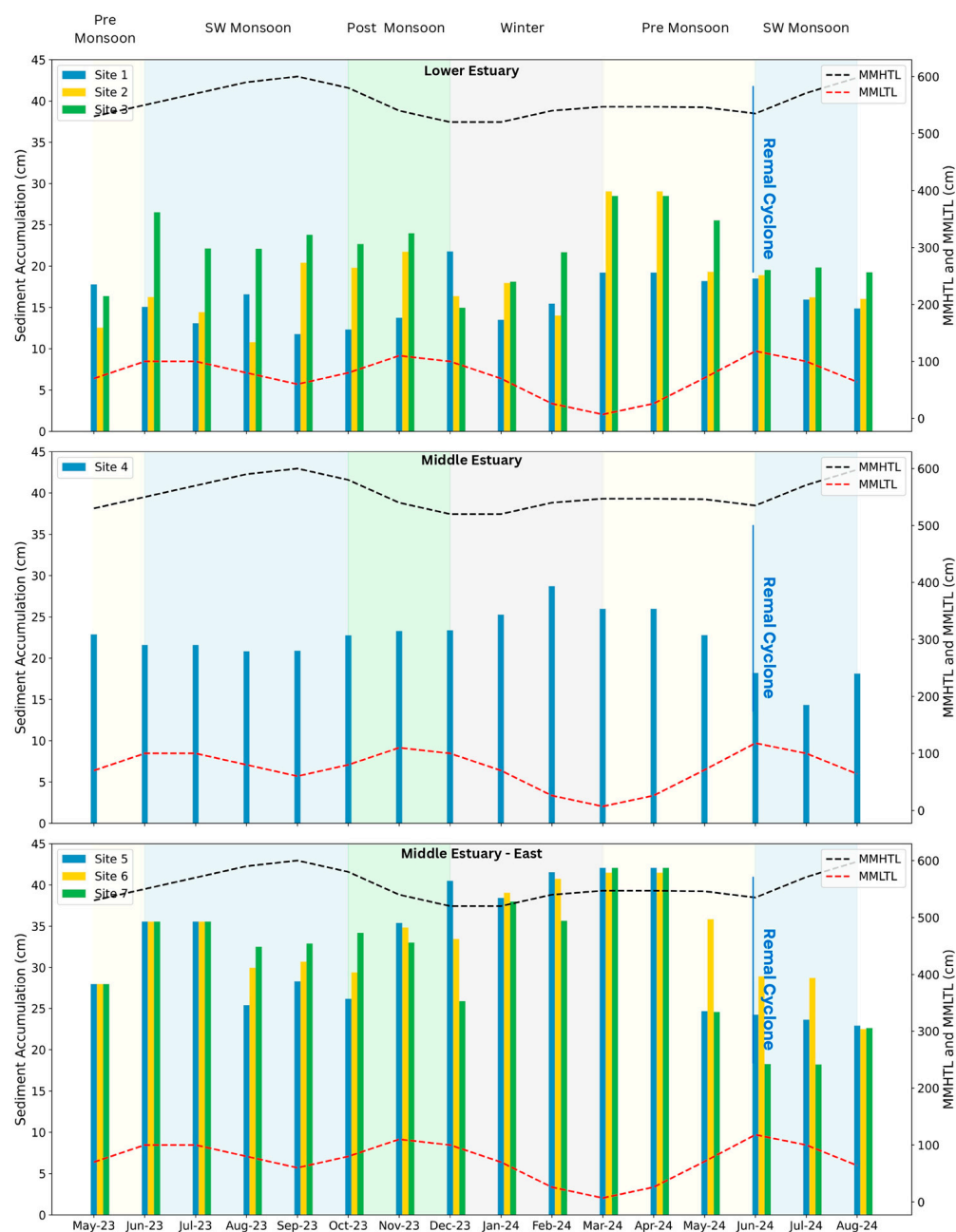


Figure 3. Sediment accumulation in each of the experiment sites for the common observation period.

Table 2. Sediment accumulation details of the total 16-month period.

Site ID	Island Location	Site Position on the Island	Average Sediment Thickness (cm)	Range of Sediment Thickness (cm)
1	Lower estuary	West	16.06 ± 2.85	11.76–21.77
2	Lower estuary	West	18.31 ± 5.11	10.80–29.06
3	Lower estuary	East	22.09 ± 4.00	14.96–28.50
4	Middle estuary	South West	22.28 ± 3.48	14.33–28.70
5	Middle estuary	West	32.15 ± 7.38	22.91–42.06
6	Middle estuary	West	33.51 ± 5.53	22.50–41.48
7	Middle estuary	East	31.19 ± 7.53	18.21–42.06

3.1. Net Sediment Accumulation over 12 Months

Between May 2023 and April 2024, the observations revealed substantial variation in sediment accumulation among the sites (Figure 4). In the lower estuary, Site 1, shielded by an enlarging sandbar, exhibited the lowest net sediment accumulation of only 1.42 cm. In contrast, Sites 2 and 3 showed significantly higher accumulation of 16.51 cm and 12.14 cm, respectively. Site 4, situated in the middle estuary and shielded by islands on both sides, recorded a notably lower accumulation of 3.10 cm. On the other hand, Sites 5, 6, and 7 consistently demonstrated high sediment accumulation, with values of 14.12 cm, 13.54 cm, and 14.12 cm, respectively.

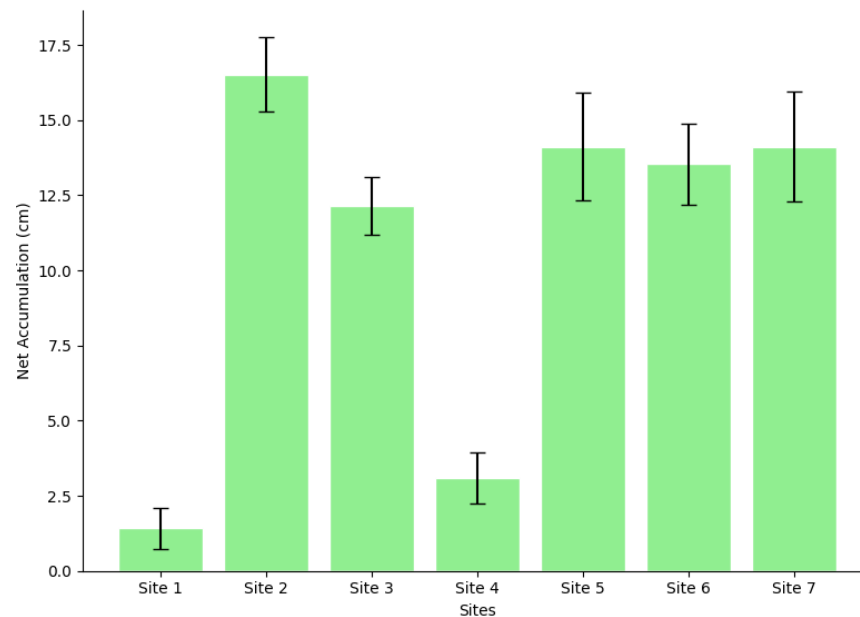


Figure 4. Net sediment accumulation after 12 months.

3.2. Granulometric Variations Among Different Estuary Locations

The granulometric analysis of the sediment accumulated at the three estuarine positions in the delta indicates a dominance of sand over clay or silt fractions at the lower estuary. In contrast, the sites farthest from the estuary mouth indicate a dominance of clay over silt and sand. These sites were dominated by clay, contributing to 46% of the total sediment composition (Figure 5). Consequently, sediment thickness at these sites was consistently higher, with peaks of up to 42 cm observed during the pre-monsoon season. However, the granulometric patterns observed in the silt traps were consistent with the patterns observed in the natural surroundings.

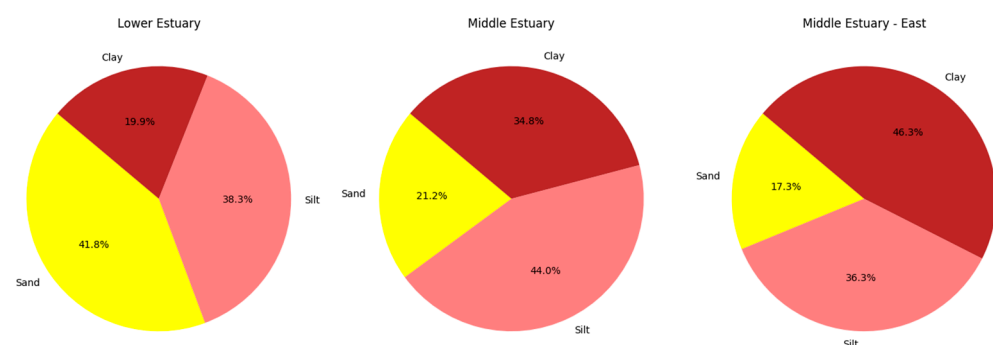


Figure 5. Average granulometric composition of sediment sampled from the silt traps over the course of the common observation period.

3.3. Growth of Mangroves and Oysters in Silt Traps

In several locations dominated by clay and silt deposition, the silt traps were colonized by natural mangrove vegetation (Figure 6 images 3 and 4), such as *Porteresia coarctata*, followed by *Sueda maritima* and *Avicennia marina*. Seeds trapped inside the silt traps remained as in the nurseries, receiving the necessary protection during the early growth stages. The best growth of mangroves was observed at Site 4 (Jamespur) and Sites 5 and 6 (Kumirmari) in the middle estuary. Site 4, however, was singularly colonized by *Avicennia marina*. Oysters were encountered in the silt trap installations, predominantly *Saccostrea cuculata*, but also *Crassostrea cuttackensis*.



Figure 6. (1) Site 4 barren patch in front of the embankment, (2) terracotta silt trap installation, (3) emergence of mangrove species, (4) growth of *Avicennia marina* in silt traps, and (5) oysters in silt traps at Site 1.

4. Discussion

Our study on sediment accumulation in the SBR, using the Living Shoreline strategy, revealed that there is significant net sediment accumulation with variability in sediment deposition and removal patterns across different sites, influenced by spatial, tidal, and seasonal factors. The experiment also enabled us to observe that sedimentation patterns were generally influenced by local factors like proximity to the sea, water level, and periodic high-intensity events. For instance, the high-intensity weather event cyclone *Remal* at the end of May 2024 curtailed pre-monsoon sediment deposition.

One of the objectives of the current study was to determine whether terracotta rings were a feasible option in the Sundarbans to retain sediment. After 16 months (May 2023 to August 2024) of observation, it was found that the terracotta rings could successfully retain sediment. Our observation also noted that the breakage of the silt traps varied between 6% and 13% at the sites since the installation (higher at Site 1 of the lower estuary). Additionally, it was observed that sediment accumulation occurred during the low water level periods, ranging from winter to pre-monsoon. The reduction in the sediment thickness due to sediment removal was higher during high water levels in the monsoon period and

corresponding tidal actions. Such a pattern of sediment deposition and removal was consistent with the study of Paul et al. (2024) [28] undertaken in the SBR.

The lower estuarine region typically accumulated more sand due to the higher energy environment generated by tidal and wave activity. In contrast, the middle estuarine region, where freshwater mixes with saltwater under lower energy conditions, was dominated by silt and clay. The cohesive properties of clay as well as the distance from the mouth of the tide-dominated estuary made the middle estuary sites less prone to sediment removal, even during the high-flow monsoon season.

Stronger flood tide action on the western coast of the islands facilitated higher sediment removal (Sites 1, 2, 5, and 6) than those on the east coast (Sites 3 and 7). However, across all three estuarine positions, net sediment accumulation was found to be double or triple the rate of annual sea level rise [9].

Pioneer mangrove species *Porteresia coarctata* naturally emerged at the middle estuarine silt trap structures, followed by *Sueda maritima* and *Avicennia marina* species. Seeds of *Avicennia* sp were also observed at the lower estuarine silt trap sites. However, higher tidal forces uprooted the newly germinated saplings at the sites closer to the lower estuary facing the open sea. Additionally, higher sand proportion in the lower estuarine silt traps might have inhibited the natural germination and growth of the mangrove seeds [29]. Survivability of mangroves in the lower estuarine silt traps was negligible. At the middle estuarine sites, the higher proportion of silt might have facilitated the newly emerging sapling roots to hold the ground. Here, survivability was near 100% except when predation by local ruminant livestock occurred. This study corroborates Nguyen (2018) [23] findings on the successful establishment of natural mangroves by trapping silt sediment through *Melaleuca* entrapping microsites, a nature-based solution. At sites with the predominance of clay, there is no mangrove regeneration.

Additionally, other biological communities, such as oysters represented by *Saccostrea cuculata* and occasionally *Crassostrea cuttackensis*, were encountered in the silt trap installations across several sites. The prevalence of spats of *S. cuculata* in surrounding estuarine waters and their colonization in the installations reflected the matrix's preferability. It also reflected the role of silt trap installations in facilitating the potential colonization of other biological groups surrounding the silt trap installations. Interestingly, the high frequency of occurrence of *S. cuculata* is also indicative of good estuarine water quality and may further suggest that the estuary is "substrate limited". Although oysters commonly attach to concrete structures, it can be argued that the introduction of the terracotta material provides a suitable substrate upon which larval oysters can attach and grow, which may be in short supply in the estuary. This also indicates that food resources required for their growth are possibly favorable across the studied sites. The colonization of these oysters may eventually help shape the formation of natural oyster reefs and act as an additional barrier against erosion as well as tidal surges. In the long run, silt trap installations may act as sites for sustaining rich bioresources such as crabs and other groups.

Our study not only encourages the use of nature-based Living Shoreline concepts for embankment toe-line protection and mangrove regeneration in the Indian Sundarbans, but also opens up new possibilities for sustainable elevation management in the sinking and shrinking mangrove region in the face of accelerated sea level rise and climate change [24,30–32].

Living Shoreline provides a sustainable and cost-effective additional toe-line protection to traditional estuarine embankments. The cost of silt trap installations made of terracotta rings, measuring 1 km in length and 6.5 m in width, is approximately USD 50,000. The installations do not require maintenance. We suggest following and maintaining the width at 6.5 m to be the minimum to replicate the design. The installation of silt traps should be

taken up in the intertidal zone from the lowest of the low-tide position up to the base of the embankment.

The Irrigation and Waterways Department (IWD) uses *Eucalyptus* poles and soil-filled gunny bags to protect eroding parts of islands in the Sundarbans. As per our interactions with IWD personnel, such structures (a kilometer long and 2–3 m in width) cost around USD 100,000, with an additional 12% cost for annual maintenance. Using bamboo instead of *Eucalyptus* for the same structure can reduce the cost to USD 65,000 per kilometer. However, as opposed to our experimental set-up, these structures do not provide any silt retention, instead, the soil-filled gunny bags disintegrate and wash away over time. It remains to be seen whether our Living Shoreline pilot project can extend the lifespan of existing embankments, which currently have an average lifespan of about 10 years [4], by providing toe-line protection. If successful, this approach could significantly reduce the annual maintenance cost of brick-armored embankments as well as to create habitat for biodiversity. Several laboratory-based studies and simulations in Bangladesh have confirmed the importance of coastal vegetation and mangrove plantations in safeguarding and ensuring the longevity of estuarine embankments in the Sundarbans, particularly against high-intensity climatic events [33,34].

Raff et al. (2023) [35] explored the mathematical feasibility of offsetting relative sea level rise in the Ganga–Brahmaputra–Meghna (GBM) delta through a nature-based solution, primarily relying on the natural delivery, dispersal, and deposition of riverine sediment. However, they emphasized the current limitations of this approach due to the construction of dams and river diversions, which have restricted the flow of freshwater and sediment into the delta. In the case of the Indian Sundarbans, most rivers and tidal creeks no longer transport significant amounts of freshwater or sediment due to their disconnection from upstream sources of the Ganges [36,37]. As a result, sediment supply to the delta margin is now primarily sourced from the sea [3,38]. Deposition of this sediment occurs in sheltered areas, with a shift in sediment composition from sand to clay and silt as one moves away from the sea, as evidenced by the diminishing availability of sand and the increasing presence of finer particles.

This study situates itself within the global discourse on Nature-based Solutions (NbSs), as recognized by the UN Environment Assembly in 2022, highlighting the significance of NbSs in addressing complex global challenges such as climate change, biodiversity loss, and disaster impacts [39]. Our approach aligns with NbS planning principles such as place-specificity, evidence-based design, integration, and equity, as it enables localized adaptation and enhances ecological resilience [40] with positive blue economy implications. In this study, the installation of terracotta silt traps in the Indian Sundarbans is an innovative adaptation of the Living Shoreline approach, facilitating sediment retention for natural mangrove growth and that of other biological communities, and protecting the existing embankments from slope instability and failure.

The findings of this pilot indicate that such green infrastructure encourages the regeneration of essential coastal habitats, offering an effective and adaptable response to environmental threats in vulnerable estuarine ecosystems in the face of climate change.

5. Conclusions

The present experiment following the Living Shoreline concept established the feasibility of silt entrapment in terracotta rings irrespective of site location in the estuaries of the Sundarban Biosphere Reserve. However, natural mangrove regeneration did not occur at all sites. Sites with predominantly sand deposition did not support mangrove regeneration, despite the saplings initially taking root. At sites with predominantly silt deposits, sapling survivability was high, unless there was predation by local ruminant

livestock. No natural mangrove regeneration was observed at the site with a predominance of clay. The terracotta silt traps, where visible, showed colonization by oysters. If sediment deposits are not removed during high-intensity weather events and mangrove plants and oysters persist over the long run, the possibility of toe-line protection to embankments and enhancing their longevity remains.

The experiment also demonstrated that compensating the rate of sea level rise in the Sundarbans through silt trapping is a possibility. Currently, in the absence of any viable protection measures at hand against the high rate of sea level rise, such experiments need a fair trial in the sinking and shrinking delta. It is heartening to note that the West Bengal Forest Directorate (WBFD) and a local NGO have initiated similar experimentation using terracotta silt traps. From the WBFD initiative, it is apparent that not all locations in the Sundarbans are suited for terracotta silt trap installations.

6. Limitations of the Study

The present pilot study in the Sundarbans Biosphere Reserve is in its very initial stage and needs further validation through long-term observation covering extreme events like storm surges and heavy rainfall. Monthly sediment monitoring in the silt traps is ongoing and will continue for at least three years to assess resilience against cyclones and multi-year tidal variability. While the first step towards establishing a Living Shoreline as a possible sediment retention strategy in Sundarbans is now confirmed, the successful encouragement of vegetation growth along with colonization of other biological groups at these silt trap structures require longer-term observation to test its sustenance as well as their role in key ecosystem processes. Within a short time span, the pilot experiment has demonstrated natural mangrove regeneration, potentially providing toe-line protection to the existing embankments. Over a longer time period, it also needs to be determined whether such nature-based solutions for silt entrapment are viable across the Sundarbans, including the non-embanked coastline of the eroding forest area. If successful, the approach may also protect the global carbon sink and tiger habitat of the Indian Sundarbans.

Additionally, the variability of sediment accumulation, composition, and removal at the lower estuarine sites is much more dynamic due to the presence of tidal bore and high-energy sea waves, which are little understood at present. As the tidal channels and estuaries of Indian Sundarbans experience variability of tidal amplitude depending on latitudinal and longitudinal position, the functionality of the present model of Living Shoreline in Sundarbans remains to be tested at a much more extensive spatial and temporal scale. A more appropriate and adaptable design for high-energy environments also remains to be explored in the future.

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