Kingdom of the Netherlands

Department of Irrigation and Waterways
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Dutch Risk Reduction Team:

*Reducing the risk of water related disasters*

# DRR-Team Mission Report

India– Sundarban

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[DRR Report Sundarban, India]

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**List of abbreviations**

| | |
|---|---|
| DoE | Department of Environment |
| DoF | Department of Forestry |
| GoWB | Government of West Bengal |
| IFI | International Financing Institute |
| I&WB | Irrigation & Waterways Department |
| NBS | Nature-Based Solutions |
| NEWS | Nature Environment & Wildlife Society |
| MDTF | Multi-Donor Trust Fund |
| MoJS | Ministry of Jalshakti |
| PPP | Public Private Partnership |
| RRI | River Research Institute |
| SIDDP | Sundarbans Integrated Delta Development Project |
| UN-OCHA | United Nations Office for the Coordination of Humanitarian Affairs |
| WASH | Water, Sanitation and Hygiene |
| WB | World Bank |
| WBADMIP | West Bengal Accelerated Development of Minor Irrigation Project |
| WRI&DD | Water Resources Investigation & Development Department |
| | |
| | |
| NR | No Regret (Immediate/now) |
| ST | Short term (0-2 years) |
| MT | Medium term (2-10 years) |
| LT | Long term (10-25 years) |

# 0. SUMMARY

The Government of the Netherlands received a request from the Government of West Bengal (Department of Irrigation and Waterways) through the Netherlands Embassy in India, for support on flood risk management of the Sundarban. This request was favourably received by the Netherlands Government who took action and organized a Dutch expert team within the framework of the Dutch Disaster Risk Reduction (DRR) programme.

The Sundarban delta (9,630 km$^2$) faces tremendous pressure by a bourgeoning human population that is economically, educationally, and socially underprivileged and inhabits an area that is mostly inaccessible due to poor infrastructure facilities. About 55% of the area is reclaimed area and 45% is protected mangrove forests. There are approximately 5.2 million people living in and around the delta. Most of the local population depends on agriculture. However, due to lack of irrigation facilities and fresh water as well as basic infrastructure, agricultural practices are primitive and dependent on seasonal rainfall, experiencing poor crop yield. Both landless as well as land owning people supplement their income by exploiting the mangrove forests, fishing, collecting, and farming tiger prawn seeds in its waters, causing damage to (marine) biodiversity.

Water security is a prerequisite to allow for any sustainable development in the Sundarban delta. To realise a freshwater environment for habitation and agriculture on the islands, dikes need to be safe and strong, where possible combined with adaptive Nature-Based Solutions. Water control structures (sluices) may need adjustment and optimalisation. The aim of the DRR-Team deployment is, together with the design engineers of the West Bengal Irrigation & Waterways Department, to examine the situation, and to provide advice on what can be done both short- and long-term.

**Long-term vision** – The aim of the Government of West Bengal is to develop a holistic and inclusive plan for the Indian Sundarban Integrated Delta Development. This long-term vision will be leading for any future sustained socio-economic development in the Sundarban. To assure that this objective can be achieved it is important to be prepared for any possible future development to be presented to the West Bengal Government to allow for an informed decision on the development strategy to be adopted. This means that the full range of potential developments should be identified and investigated. This will also allow for elaborating different adaptive strategies to be prepared from a water security point of view.

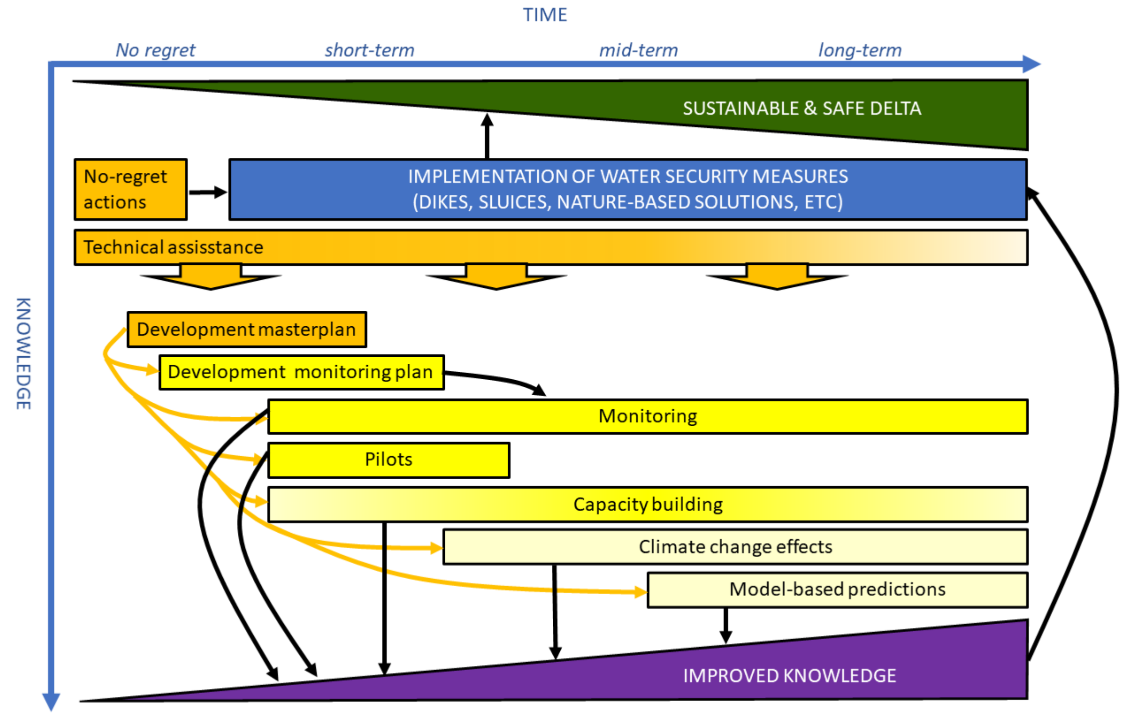
**Flood Resilience** – The risk of flooding from dike breaches along the river and coastal stretches of the Sundarban is significant. Efforts to strengthen the area's line of defences need to go hand in hand with the ongoing activities of building resilience for the people in the delta. During the last typhoon Amphan the existing 1800km diking system breached at ca. 700 locations and land flooded, causing disruption and damage to people and their livelihoods. The challenge for the future for Sundarban is to become a safe place for its people. Coastal resilience is all about being prepared, strong embankments and sea dikes are needed. The design of an embankment or sea dike shall be a multidisciplinary exercise in which hydraulic, geomorphological, and geotechnical aspects are considered and also international best practices and guidelines are used. A risk-based approach for the delta is needed, finding the right balance between strengthening existing embankments and sea dikes and realigning to these structures along new routes, considering the delta's morphological dynamics.

**Delta morphodynamics** – The Sundarban delta is dynamic at various temporal and spatial scales. At the largest scale, the delta is influenced by loss of connectivity between the Ganges river and Sundarbans delta (especially leading to shortage in water and sediment) and land reclamation (leading to large-scale tidal amplification). Tidal

amplification strongly modifies tidal channel configuration, mostly resulting in bank erosion. The reduction in sediment supply following the diversion of the Ganges river to its present main outlet in Bangladesh initiated the structural erosion of the coastlines facing the Bay of Bengal. Knowing the mechanism responsible for erosion is important for designing mitigating measures and strength of the embankments. Structural erosion resulting from a sediment deficit requires very strong embankments, and may be better mitigated with managed retreat. Erosion resulting from changes in tidal dynamics (amplification or network reorganization) is also better mitigated with managed retreat but may also be reduced with promoting foreshore sedimentation. Bank erosion resulting from laterally migrating rivers is preferably mitigated with foreshore sedimentation, while bank erosion along infilling channels will gradually slow down naturally.

**Nature-Based Solutions** – The Sundarban Delta has a large potential for the implementation of Nature-Based Solutions (NBS). The main NBS for this area should focus on trapping sediment within the delta in the right places. These measures counterbalance sea-level rise and subsidence and create a gradual transition from land to sea with a protective mangrove greenbelt, dampening waves and peak flow velocities along riverbanks. The Bay of Bengal provides a large stock of sediment allowing sediment trapping strategies to build and raise new land in the Sundarban Delta, at least on a decadal timescale – at longer timescales accelerated sea level rise may lead to sediment shortages.

**Main conclusion and way forward** - Key to the development of a sustainable and safe Sundarban is to ensure water security by developing resilience against floods, the creation of a freshwater environment on the islands and restoration of fresh water to the Sundarban Delta. A following visual of the roadmap provides an overview of recommended steps on short-, mid- and long-term activities. For further detailing of the steps, the reader is referred to Chapter 2 and Chapter 3 of this report.




*Relation to existing programs/projects and research:* Rural minor irrigation with involvement of Water User Associations is being implemented by the West Bengal Accelerated Development of Minor Irrigation Project funded by the World Bank. A main activity in the Sundarbans is the realisation of water detention structures for rainfall harvesting. Creation of a freshwater environment in conjunction with improved minor irrigation and drainage management will greatly enhance the outcome of the project. Solidaridad is active in the Sundarbans with focus of on provision of clean water and preventing water pollution. A Letter of Intent has been signed between the West Bengal and the Netherlands which may result in activities under Partners for Water 5.

# 1. General Background

## 1. General background

### 1.1. Introduction

The north-eastern shores of India and Bangladesh are home to the Sundarban, the world's largest contiguous mangrove forest. The Indian Sundarban is spread across approximately 9,630 square kilometres, of which 5,363 square kilometres is reclaimed area and 4,267 square kilometres are protected mangrove forests. A further 6,000 square kilometres of protected mangrove forests are spread across neighbouring Bangladesh. The Indian administrative region of Sundarban (see Figure 1-1 and Figure 1-2) lies within the State of West Bengal. The entire area is a conglomeration of river channels, creeks and about 102 islands. Currently 54 islands are inhabited while the remaining 48 islands remain forested. The Indian Sundarban is divided into reclaimed and non-reclaimed parts. The reclaimed Sundarban in West Bengal comprises six C.D. Blocks of North Parganas and 13 Blocks of South Parganas and is mainly used for agricultural purposes.

*Figure 1-1: Administrative blocks in the Indian Sundarban.*

The Sundarban delta faces tremendous pressure by a bourgeoning human population that is economically, educationally, and socially unprivileged and inhabits an area that is mostly inaccessible due to poor infrastructure facilities. There are approximately 5.2 million people living in and around the Sundarban delta. In the absence of any industry, most of the local population in the Indian Sundarban depends on agriculture. However, due to lack of irrigation facilities and fresh water as well as basic infrastructure, agricultural practices are primitive and dependent on seasonal rainfall, yielding poor crop and acts as an erratic source of livelihood. Both landless as well as land owning people supplement their income by exploiting the mangrove forests, fishing, collecting, and farming tiger prawn seeds in its waters, the latter particularly causing large scale damage to marine biodiversity.

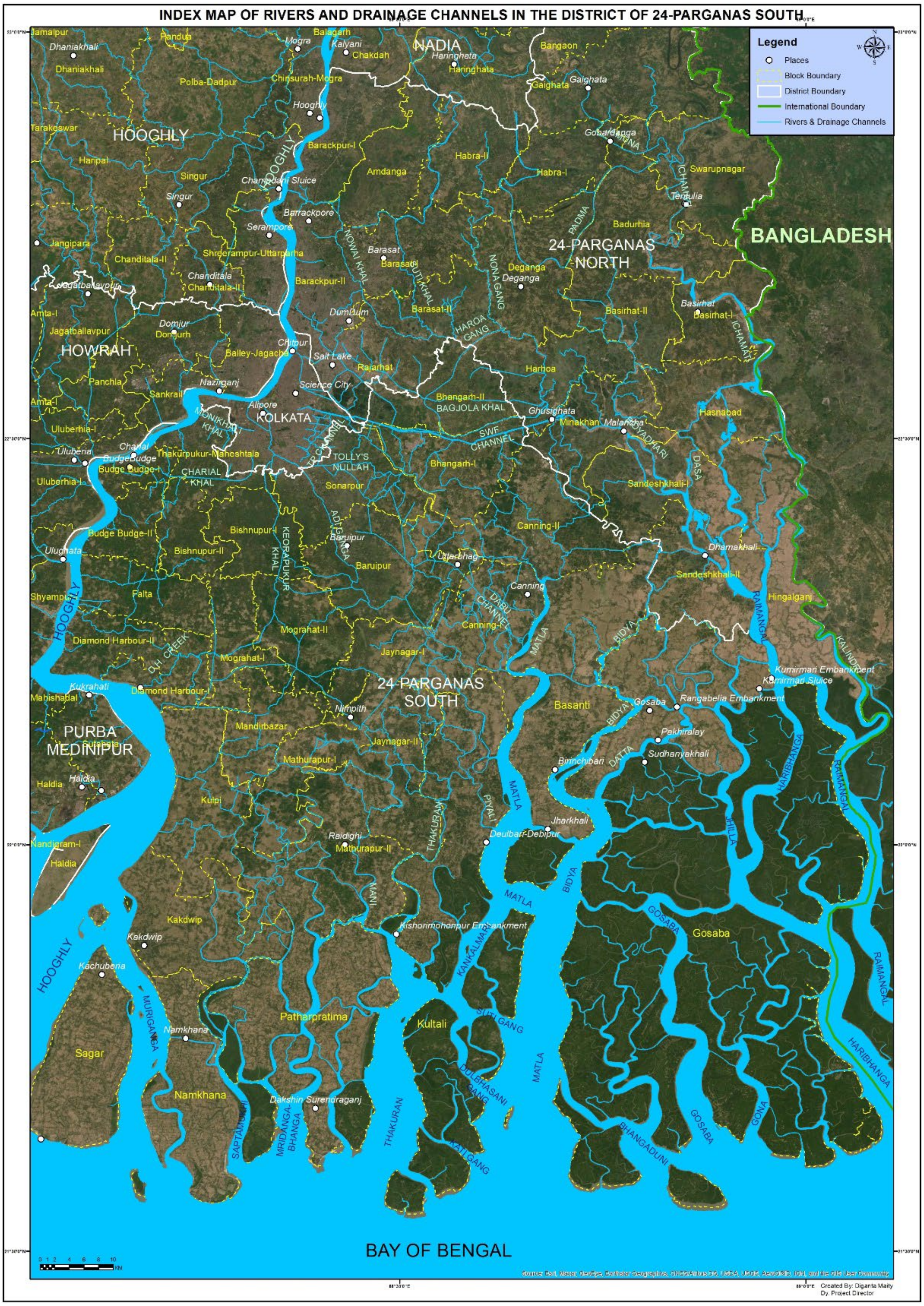



*Figure 1-2: Map of the Sundarban' water system.*

Development of the Indian Sundarban in West Bengal has been a challenge in the public policy domain. The Sundarban delta has been subject to a large number of human interventions in the past centuries, which have greatly and often negatively impacted the resilience and vulnerability of the area. It is becoming increasingly clear that there is a need to develop a holistic, nature-based and inclusive plan for the Indian Sundarban Integrated Delta Development. The realisation stems from the fact that different pieces such as embankment protection, agriculture, pisciculture, livelihood etc in Sundarban are all interrelated and much of these linkages are yet to be appropriately identified and weaved into a plan.

Earthen embankments were built along 3500 kilometres long riverbanks and sea shores. However, the islands of the Sundarban are extremely vulnerable to flooding by storm surges during cyclones and high river discharges when they come together during the monsoon periods. In the recent period the Sundarban experienced several serious cyclones. Latest was in May 2021 with cyclone *Yaas* with unprecedented High Tide Levels and strong winds. Several sea dikes collapsed and were overflown with disastrous results on the people, loss of houses and infrastructure. Due to proper functioning of the early warning system and a well organised evacuation of people from the flooded area the number of casualties was low. Part of the vulnerability of the Sundarban arises from uncontrolled human interventions in the past centuries (section 1.2), in the future further aggravated by climate change (section 1.4). These interventions, in combination with the improper construction and maintenance, has led to large-scale degradation of embankments – at present the length of effective embankments and dikes is not more than 1800 km. Breaches and overtopping of embankments are common, especially when landfall time of a cyclone synchronises with high tide.

Key to the development of the Sundarban is to ensure water security by developing resilience against floods, the creation of a freshwater environment on the islands and restoration of fresh water to the Sundarban delta. To achieve these aims, uncoordinated sectoral activities which may give sub-optimal short-term results at unnecessary high cost need to be avoided, requiring a holistic approach. Without such an approach, a slow-paced disaster will take place and people will migrate from the area as continued salt intrusion and damages will make the Sundarban unhabitable and thus foregoing on improvement of livelihood of the local people, on the potential contribution the Sundarban can provide in food security and to the socio-economic improvement of West Bengal as a whole.

Hence, water security is a prerequisite to allow for any sustainable development in the Sundarban water system. To realise this, dikes need to be safe and strong, and the water control structures (sluices) at the outlets of the major creeks need reconstruction and optimalisation. To share international experience and insights on integrated planning, design, and construction on the above issues, based on a request from the Government of West Bengal to the Government of the Netherlands, a team of four Dutch (DRR) experts has visited the West Bengal Sundarban from 17 to 28 April 2022 and exchanged views with West Bengal experts on the feasibility of short-, mid- and long-term solutions for the Sundarban and the dynamic water system of which it is part.

The present report builds on the Draft Concept Note "Sundarban Integrated Delta Development" (WB I&WD/PUM, 2022).

## 1.2. System understanding

The Sundarban region is a trans-national area composed of pristine mangrove forest surrounded by an area of reclaimed land. Most of this peripheral zone, in both India and Bangladesh, was cleared of mangrove forests between 1841 and 1954 (Nishat, 2019). This has led to a drastic change in river courses, sediment and fresh water supply, and subsidence rates.

### 1.2.1. Historic development

The Sundarban is part of the Ganges-Brahmaputra delta, one the world's largest delta complexes. The present-day Hooghly river used to be the main outlet of the Ganges river, providing a large amount of sediments and fresh water. The main outlet of the Ganges has gradually shifted eastward (with the current main outlet being the Meghna Estuary in Bangladesh), with former river outlets between the Hooghly and the Meghna becoming tide-dominated estuaries connected to the Ganges river through smaller distributaries providing fresh water and sediments. The suitable salinity conditions enabled the development of the extensive Sundarban forest. But because of the gradual eastward migration of the main source of sediment supply, the coastline of the former outlets facing the Bay of Bengal are now eroding (Figure 1-3), up to 12 km since 1776 (Nishat et al., 2019) which corresponds to 50 m/y.

The large changes that took place in the last centuries are illustrated with Figure 1-3. Historically, the main outlets (largely running in the North-South direction) were connected to the Hooghly river via river systems largely oriented in the East-West direction. In 1794, the Sundarban region was connected to the Hoogly river via the Bidyadhari river and the Jamuna/Ichamati river. By the end of the 19th century the Bidyadhari river was still connected to the Hooghly via the Tolly's Nullah (Batholomew, J.G., 1893) but by 1930 completely disconnected (Survey of India, 1930). The Bidyadhari river drained an extensive lake and swamp area which were reclaimed later, and after complete disconnection the river rapidly silted up (Maitra, 1969). Fresh water also flowed from the Ganges river via the Mathabhanga and then Ichamata river. These rivers fed the various tidal estuaries (Thakuran, Matla, Haribanga, Raimangal) with fresh water through an intricate channel network of bifurcating and converging rivers. The Bidyadhari and Jamuna rivers became progressively more disconnected from the Hooghly; at present they are completely disconnected. Only the Ichamata river still receives 5 – 10 $m^3/s$ via the Mathabganga river; the Sundarban delta therefore primarily receives fresh water through rainfall. This reduction in freshwater discharge must have greatly increased the salinity in the Sundarban. No data is available for the western Sundarban, but it has been observed that a dry season reduction of flow in the Gorai River (Bangladesh Sundarban) in the 1970's from ~200 to ~100 $m^3/s$ already led to a sharp increase in the reclaimed Sundarban, from below 2 ppt (the salinity limit allowing agriculture) to more than 10 ppt (Mirza, 1998). The impact must have been greater in the Indian Sundarban, which were nearly completely cutoff from fresh water supply.

The reduction of freshwater discharge greatly influenced the morphology of the connecting rivers (running from West to East), which completely silted up. The tidal estuaries (oriented from south to North) are more influenced by modified tidal dynamics than by the reduction in river discharge. The reclamation of the swamps and mangrove forests in the 19th and 20th centuries impacted the tidal dynamics (amplitude, tidal discharge, degree of asymmetry) by reducing the volume of water that can be stored of the intertidal plains. This change in tidal dynamics reshaped the tidal estuaries and channel network in the Sundarban areas, leading to development of new channels and infilling of others (see the large differences in channel configurations between 1794 and 2022 in Figure 1-3). Such processes are slow, and morphological adaptations may require many decades or even centuries. This means that the Sundarban delta may still be adapting to reclamation works or other interventions carried out many decades or even a century ago. Branches in the Bangladesh part of the Sundarban which have been closely monitored for over the past 80 years reveal a continuous adaptation of the tides and channel network, with a range increasing from 2-3 meter around 1960 to 4-5 meter around 2020, which resulted in structural erosion of various embankments (van Maren et al., in review). Although less detailed continuous observations are available in the Indian Sundarbans, historic observations do extend further back in time, revealing that tidal changes have been alarmingly large.

### 1.2.2. Tidal amplification

The tidal range in the Sundarban is 4-5 m at the mouths of the various estuaries and their range increase as the tides propagate inland (up to 7 meter in the Bidya and Matla rivers (Chatterjee et al., 2013). The Highest High Water Level (caused by tides, not by storm surges) at fort Canning rose from 1.884 m in 1865 to 3.849 m in 1930 and to 7.08 m in 2011 (Chatterjee et al. (2013) and references therein). The tidal range therefore used to decrease (to nearly 0 at the landward limit of the original Sundarban such as Canning - Chatterjee et al., 2013). The tidal range has therefore greatly amplified, with as much as 7 meter at Canning, leading to a sharp increase in tidal current velocities and water level variations (both destabilising embankments). This tremendous increase in tidal influence likely reshaped the Sundarban outlets from the relatively small channels they were in 1794 into the fairly wide estuaries they are now (Figure 1-3). The only way to predict future embankment failure is through large-scale and smaller-scale system understanding (see section 2.2.1 on erosion for more details).

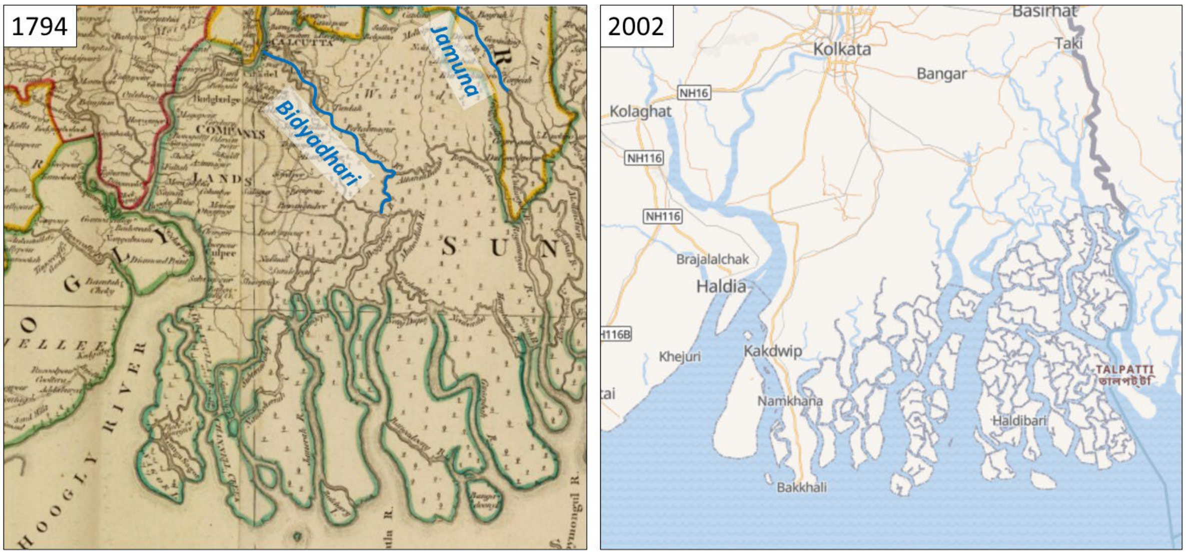



*Figure 1-3: Map of the eastern GBD in 1794 (Laurie & Whittle, 1804) and 2022 (OpenStreetMap); both extracted from Davidrumsey.com. The course of the Bidyadhari and Jamuna rivers are highlighted in blue.*

### 1.2.3. Subsidence

Under natural conditions the Sundarban is regularly flooded by the tides depositing their sediment around high water. This allows these environments to keep pace with rising sea levels or subsiding soils. Embanked areas are not regularly flooded, and therefore sea level rise and soil subsidence lead to progressively larger differences between the ground level and sea levels. Soil subsidence is composed of three components: tectonic subsidence of the deep subsurface, ground water extraction (typically from depths of several 100's m), and compaction of the shallow subsoil (top 10 m). An extensive review of observed subsidence rates in the whole Ganges Brahmaputra delta by Brown and Nicholls (2015) shows that highest subsidence rates in West Bengal occur in Kolkata (10-20 mm/y, largely because of groundwater extraction). But also in the mangrove-covered Sundarban as well as the reclaimed Sundarban delta and east bank of the Hooghly river subsidence rates are typically between 2 and 5 mm/y. This is fairly close to Brown and Nichol's mean value of 3.9 mm/y for the whole delta, making their average value a reasonable best estimate for actual subsidence. The subsidence rates between the pristine Sundarban and reclaimed Sundarban is not large, implying that the large elevation differences between reclaimed and non-reclaimed lands in the western Sundarban (0.5 – 1 meter, suggested by Figure 6 in EC (2021)) is not caused by faster subsidence, but lack of sedimentation. On top of subsidence, the average water levels are increasing due to global sea level rise, which presently amounts to 3 mm/yr in the Ganges-Brahmaputra delta (Pethick and Orford, 2013). The total relative sealevel rise in the Sundarban delta is therefore around 7 mm/y. Although an important number, it is much less than the increase in water levels arising from changing tidal dynamics (as elaborated above).

### 1.2.4. Summary

The main aspects related to system understanding, relevant for the Sundarban delta, may therefore be summarized as follows:

- The Sundarban used to be connected to the Hooghly and Ganges rivers but is now disconnected. As a result, the rivers connecting the Sundarban with the Hooghly river silted up and the fresh water supply to the Sundarban delta sharply reduced. The impact of this disconnection on the morphology of the estuaries running from South to North is probably limited.
- The reclamation of the swamps and mangroves and creation of artificial channels north(west) of the Sundarban forest influenced tidal dynamics in the estuaries running North to South, which in turn led to a change in the channel network (silting up of some channels and bank erosion along others).
- The tides have amplified (from 0 to up to 7 meter) in the estuaries, reshaping the Sundarban morphology and destabilizing embankments through higher flow velocities and water level variations.
- The embanked Sundarban are sinking with 7 mm/y relative to the sea level, but the pristine Sundarban keep pace with rising water levels by sedimentation. Changes in tidal levels are probably more important for high water levels than changes in relative sea level rise.

## 1.3. 'Room for the River' and managed realignment

The above analysis reveals that one of the key issues in the Sundarban delta is a loss of space for the various river systems on various scales. We will shortly evaluate two potential policy options for dealing with a structural shortage of space for hydraulic systems: 'Room for the River' and 'management realignment'.

### 1.3.1. Room for the River

'Room for the River' is a possible solution for the lost connection between the Hooghly river and the Sundarbans area. From an integrated water management point of view and considering the objective of creating a healthy river system as part of a dynamic delta, consideration needs to be given to this entire water system which also includes the Kolkata metropolitan area. Restoring these connections is beneficial for the Sundarbans (providing fresh water) and for the Kolkata region (improving drainage and water quality). A major issue in this respect is the urban development taking place South-East of Kolkata. In this area urban housing and industry encroaches existing canals and river branches thus creating blockages in the water system and preventing proper freshwater flow into the Sundarban. At the same time, at places, it hampers the drainage of storm rainfall from the City of Kolkata and seriously deteriorates the ecological conditions of the rivers with negative effects for the health of often the poorer parts of the population.

A potential blueprint for restoration of these connecting rivers is the Dutch policy of "Room for the River". Like what is happening in West Bengal also happened in The Netherlands. Over time, a lot of land has been taken from larger rivers and smaller streams. In the latter case the streams were sometimes fully blocked, and the land used for urbanization and industry without any regard for the water management and environment of the area. The result was increased risk against flooding and deterioration of the environmental and living conditions. At the same time the land now prone to flooding had a higher socio-economic value making the cost of the damage, when flooding occurs, substantially higher. In the mid-nineties of the last century, after some serious river floods occurred, a paradigm change took place in the, up till then, adopted approach on flood prevention. The principles of 'living with water' and 'Room for the River' were introduced, and a regulatory framework formulated and put into law. The aim of the policy is to improve sustainable protection against flooding and at the same time improve the overall environmental condition of the river system and its surroundings. In practice this means for the fluvial dominated part that any encroachment on or inside the river and canal embankments is strictly prohibited by giving the river space to flow under storm rainfall conditions and maintain an environmental flow in the dry period to keep the river healthy. To translate this in practice the "Room for the River" project has been implemented and completed by 2018 (https://www.dutchwatersector.com/news/room-for-the-river-programme).

As mentioned, the same occurs in West Bengal. At some locations bottle necks have already developed or even total blockage occurs. These encroachments need to be removed and sometimes it also requires interventions such as opening blockages by dredging, removing obstacles such as local bridges, moving embankments outwards from the river or creating parallel flood channels. An advantage in West Bengal is that the historical alignment and the, at that time, related water body and area may be well 'vested land' allowing the West Bengal Government to use this land for improvement of its much-needed integrated water management of the urbanized and industrialized area (including the areas used for large scale environmentally hazardous and unsustainable aqua culture). The policy of "Room for the River" could be extended beyond the urban developments in the Kolkata metropolitan area, so that it extends to the entire state where developments hamper safe and healthy rivers and canals. An integrated master plan to formulate an adaptive approach together with the regulatory framework is recommended. This is to form the basis for the planning and implementation of the required interventions in a coordinated manner. On the short term no-regret interventions can be identified to alleviate the most pressing and risk prone areas from both a flood protection as from an ecological perspective.

### 1.3.2. Managed realignment

Managed realignment is the strategic retreat of primary defenses from a position that is considered undesirable to protect from a financial, physical, and/or ecological point of view. For the Indian Sundarbans this may apply to embankments and sea dikes which are so much threatened by erosive properties that the costs of their upgrading exceed the costs associated with their breaching (risk). Deciding whether managed realignment should be implemented is primarily based on a risk analysis. Risk is herein defined as the probability of failing (1%, 10%, …) multiplied with the damage of flooding (in Rupees, Euro). Even a relatively inexpensive embankment or sea dike may therefore be realigned if the hinterland it protects has little economical value.

However, managed realignment also has additional benefits. First, it offers a foreshore where mangroves may develop, protecting dikes and providing nursery for fish. Embankments with mangrove-fringed foreshores require smaller embankments compared to systems without foreshores, and may be beneficial for fisheries, and hence improve the economic value. Secondly, such foreshore trap sediment, further strengthening the landward (realigned) embankment. Such sedimentation processes may thereby even trigger positive feedback mechanisms which counteract erosion of the original embankment. Thirdly, realignment creates space for the incoming tidal wave, thereby damping its propagation speed and amplitude. As such it may mitigate the amplification of the tide, which is likely one of the key mechanisms leading to bank erosion in the first place.

### 1.4. Impact of climate change

Climate change models (as used for IPCC, 2019) suggest that besides the precipitation in the catchment area of the Ganges will increase, resulting in a significant increase in its river discharge (Eckland et al., 2020). But these models also consistently predict that the dry season will become dryer after 2050. Before 2050 such changes are small. By 2050 the sea level of the Northern Bay of Bengal is projected to be 0.18 m higher than in the year 2000 (RCP4.5 scenario; stabilizing CO2 emissions) to 0.22 m higher (RCP8.5; emissions remain constant); predicted sea levels are 0.49 (RCP4.5) to 0.76 m (RCP8.5) higher in 2100 (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool).

Tropical cyclones are important for flooding and wave overtopping during storm surges. Climate change will probably lead to a shift towards more severe storms in the Bay of Bengal, resulting in a reduction of moderate cyclones and an increase in severe cyclones (Knutson et al., 2020, 2021). An increase in temperature of 4$^{o}$C (expected around 2050 in the RCP8.5 scenario and end of 21st century with the RCP 4.5 scenario) will lead to an increase of wind speed of 1-10%. An increase of 1.6% in tropical wind speed (and a corresponding 25% increase in frequency of high-category storms) may lead to an increase in storm surge height of 6-11% and wave height of 6-9% (Leijnse et al., 2021).

Summarising, the impact of climate change will give an increase in mean water levels, storm surge heigh and wave height. The total precipitation and therefore river flow through the Ganges will rise, but the discharge during the dry season will become less after 2050. Both the hydraulic pressure on the embankments as well as freshwater shortage in the Sundarban will therefore only increase as a result of climate change.

### 1.5. Social and Environmental Safeguards

The Sundarbans Delta Development will require a multitude of interventions in the prevailing social and ecological structures. Each intervention needs to comply with existing relevant national and state regulations before plans can be approved and implementation takes place. The holistic masterplan will need to be accompanied by a Strategic Environmental Social Impact Assessment (SESIA). For individual interventions specific ESIA's will need to be prepared. The balanced socio-economic development of the Sundarbans area requires an understanding and specific attention to improving the livelihood of socially and economically deprived groups of in particular the disabled, women, unemployed youth and the elderly but also landless farmers and fishermen. The SIDDP will need to focus, in a holistic way, on integrated rural development with water security measures as main catalysts providing opportunities for ensuring social and economic inclusion of the afore mentioned groups. The development plan is to think through of a set of predefined key inclusion questions and to identify relevant responses or adaptations. The status of the socio-economic and environmental issues prevailing in the Sundarbans are extensively elaborated upon in the reports prepared by Sánchez-Triana et al. (2014) and WB I&W/PUM (2022).

# 2. Analysis

# 2. ANALYSIS

## 2.1. Long term vision

The aim of the Government of West Bengal is to develop a holistic and inclusive plan for the Indian Sundarban Integrated Delta Development. The plan will have to yield a clear political and administrative long-term vision on how best to guide a sustainable development of the region.

The benefit and necessity of such a plan and its implementation is best understood when considering present conditions. The majority of the local population in the Indian Sundarban depends on agriculture. However, due to lack of irrigation facilities and freshwater as well as basic infrastructure, agricultural practices are primitive and dependent on seasonal rainfall, yielding poor crop yields which therefore act as an erratic source of livelihood. Both landless as well as land owning people supplement their income by exploiting the mangrove forests, fishing, collecting tiger prawn seeds in its waters, the latter particularly causing large scale damage to marine biodiversity, and farming. Considering prevailing extremely poor safety against cyclones and high tides and saline conditions of the land due to salt intrusion through creeks and overflowing of dikes, the overall vision needs to include a specific vision on realising water security.

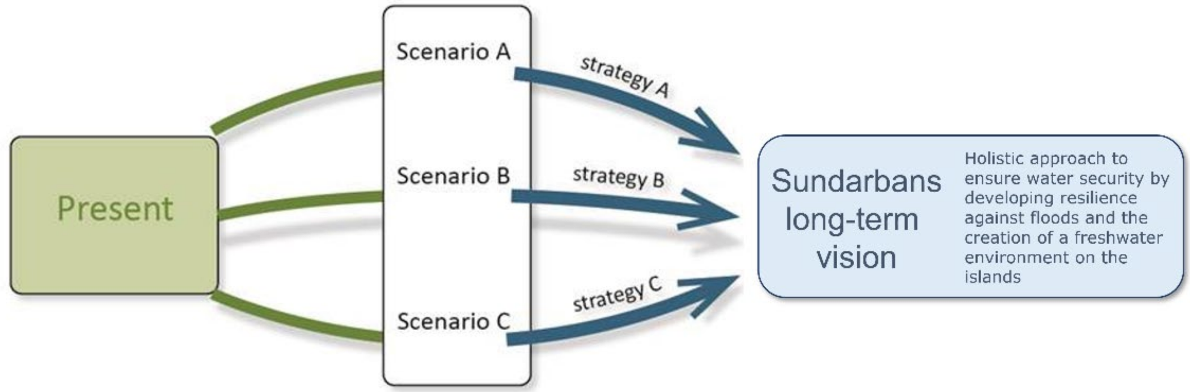



*Figure 2-1: Multiple strategies for realizing a long-term vision.*

The long-term vision is leading for any future sustained socio-economic development in the Sundarban (Figure 2-1). To assure that this objective can be achieved it is important to be prepared for any possible future development to be presented to the West Bengal Government to allow for an informed decision on the development strategy to be adopted. This means that the full range of potential developments should be identified and investigated. This will also allow for elaborating different adaptive strategies to be prepared from a water security point of view.

The Sundarban Integrated Delta Development – Draft Concept Note 8th March 2022 (Ref. WB I&W/PUM, 2022) provides a good overview of the present socio-economic and water security status of the Sundarban and touches amongst others on food security and biodiversity, social and environmental safeguards, social inclusion and gender. Together with this report, with its focus on water security it provides integral background information on which the development of scenario's can be based and eventually yield a long-term view for the preferred development of the Sundarban.

**Principles of Adaptive Delta Management**

1. Identify main external trends and drivers and consider their uncertainties and potential tipping points as well as risks and impact characteristics
2. Perform a holistic analyses of national and regional (hotspot) issues, challenges, knowledge gaps, with awareness of the need for a multi sectoral scope and stakeholder contributions
3. Adopt a long-term approach, including a vision, scenario's and strategies to manage future uncertainties and connect short term decisions with long term objectives (form adaptive pathways)
4. Elaborate national and regional (hotspot) planning and stakeholder involvement, explore linkages between (public and private) investment agenda's of different sectors and stakeholders
5. Arrange institutionalized ownership and stimulate multi sectoral coherence and coordination
6. Create provisions to ensure progress and financial and institutional continuity of implementation; updating and adaptation of strategies and actions where needed

*Figure 2-2 Principles of Adaptive delta management (based on Bloemen et al).*

Apart from the development of a long-term view with respect to water security, the permanent threat of cyclones and high tides requires planning for short-term and medium-term measures. As stated before, water resilience and water security are a pre-condition for any other sustained development to take place. It can be safely said that any well-designed intervention in this respect can be considered as no-regret (a measure which always fit within the mid-term and long-term visions). However, in the design criteria the principles of Adaptive Delta Management must be incorporated to allow for future adaptations needed due to changed conditions as a result of delta dynamics and climate change. In addition, environmental and social impacts will have to be taken into account in an inclusive way.

Vision development is important in formulating a scientifical and consistent development objective. In the below table general steps are presented to arrive from vision to implementation.

## 2.2. Flood resilience

### 2.2.1. Current situation

For flood resilience, the Sundarban area relies on embankments and sea dikes. Nowadays the total length of embankments and flood defence structures in the Sundarban is around 1800 km. The state of some of these structures is poor and their condition became even worse after cyclone Yaas. Dike designs in earlier years were below standard, for example with steep slopes and without any filter layer underneath the concrete slab or brick block protections, resulting in failure of the outer revetment. Outdated manuals are in use without references to good international practices. Also, proper design was hampered by considerations of limiting cost and short cuts were allowed during execution of the works due to condoned practical on-site construction and implementation constraints.

In March 2021, new recommendations were laid down in IWD (2021). More robust dike constructions were proposed, and geo-synthetic textile filter was introduced to be placed underneath the concrete – brick block protection. UC Bullah are recommended as toe protection. Porcupine spurs are recommended to be placed in front of the dike and where possible and provided a required volume of sediment accretion has occurred, the planting of mangroves. Where extra severe conditions exist, tetrapods are used for dike protection or protection of the toe.

The recommendations have been adopted in the new dike designs and are being implemented in the field. When comparing the recommendations with good international practice on sea dike design and construction some further study and knowledge exchange could be considered in view of still unsolved failure mechanisms which can be observed on site - notably still poor filter and toe protection design and on-site execution. With investment of US$ 1 million for one kilometer of sea dike it is worthwhile to reconsider design and execution practices to avoid lost investments when the rehabilitated and new dikes will fail again with the next serious cyclone.

### 2.2.2. The challenge

The risk of flooding from dike breaches along the river and coastal stretches of the Sundarban is significant, also on an annual basis. Efforts to strengthen the area's line of defense need to go in parallel with ongoing activities in building resilience for the areas and its people. During the last typhoon, at 700 locations the diking system got breached and areas got flooded. Localized flooding can be disruptive, while the more extreme events could also cause fatalities. The challenge for the Sundarban is to be a safe place for its people. Coastal resilience is about being prepared when the next event occurs. Besides structural measures (e.g. building dikes), non-structural measures are a very important part of the way forward. Sustainable planning, zoning of flood prone areas and emergency response activities and procedures will lift the area's resilience.

The Sundarban embankments and sea dikes have, especially in recent years, suffered heavily from storm surges caused by cyclones and high river floods. Observations from our site visit can be summarized as follows. There is an absolute need to invest in strong, sustainable, and future proof embankments. Moreover, there are opportunities to include mangroves as a vegetated foreshore, which can contribute to flood safety and have potential in locations of dike realignment. Realignment might be needed at eroding riverbanks. Lastly, it is important to have a set-up for planning and zoning, strengthening the policy, governance and enforcement when living with water.

During our field trip and different meetings with officers from the Department of Irrigation and Waterways better insight was gained in the challenges the Sundarban is facing. Besides the breach locations and the pace of the subsequent reconstruction works, also the size and complexity of building, (re)constructing embankments and levees became clear. It is important to take on board all lessons learnt while moving forward. Another insight out of the fieldtrip and the numerous conversations is the need for prioritization. Where to start first? A programmatic risk-based approach to this is crucial, by prioritizing the realignment and reconstruction of the dike improvement works over time.

### 2.2.3. Observations and lessons learnt

The most relevant observations from the site visits, the meetings with the officials from the Department of Irrigation and Waterways and our understanding of the report of the IWD (2021) are summarized in the Table 1 and the figure below.

1. *An absolute need to invest in strong, sustainable and future proof embankments.* The required level of protection, the alignment of the embankments, sea dikes and its function are important aspects to be considered per stretch. Based on a cost benefit assessment, value of protected lands should be balanced with the investments in flood protection works.
2. *Opportunities to include mangroves as a vegetated foreshore, which can contribute to flood safety and have potential in locations of dike realignment.* Nature-Based Solutions (see Ch. 2.4) should be integrated in the design of flood protection structures. This should not be confused with allowing trees to grow in or close to the slopes of the embankments. It is recommended to keep at least 5-10 m out of the dike toe free of trees. Nature-Based Solutions, e.g. a foreshore vegetated with mangrove forest can in a sustainable manner, reduce impact of wave action and therefore contribute to the reduction of crest level and footprint of the embankments.

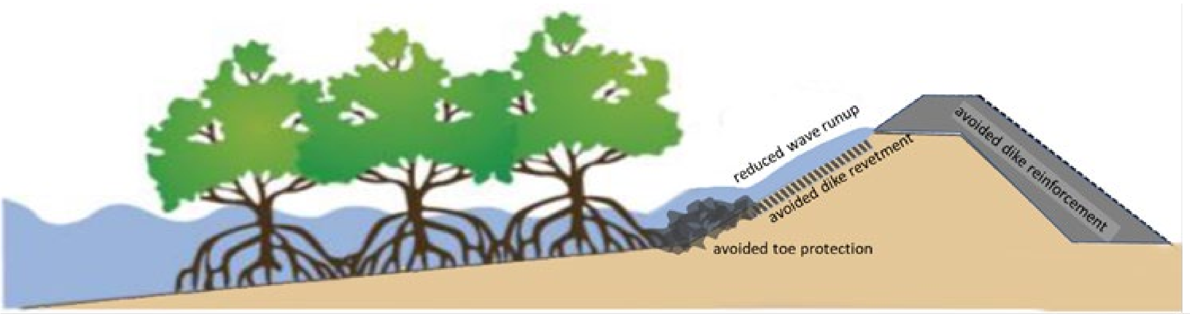
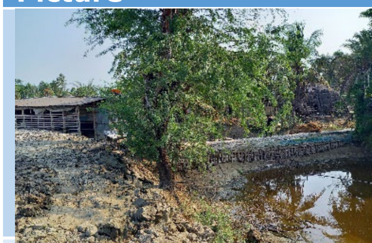



*Figure 2-3: Combination of Nature Based foreshore solution in combination with dikes (adjusted from World Bank, 2017).*

3. *Realignment might be needed at eroding riverbanks.* To counter the impact of erosion and reduced tidal amplification (see Ch. 1.2 & 2.3), the most sustainable way forward seems to be the realignment of some of the embankments. The vulnerability mapping on potential areas, susceptible to strong erosion in the future, will outline these sites. Temporary measures such as porcupines will slow down the process, but more strategic long-term measures are necessary to safeguard the people and their lands. Realignment is a complex process. All stakeholders need to be consulted and included in the process in order to arrive at a sustainable solution.
4. *Development of a pathway for planning and zoning, strengthening the policy, governance and enforcement when living with water.* Operation and maintenance are crucial parts in the management of assets (e.g., embankments, outlet sluices, gates). A plan for monitoring and control needs to be available and executed, including frequent surveying and visual inspections of the embankment, the sea dikes and their foreshore and hinterlands. This will enable the Department of Irrigation and Waterways to quickly respond in case of repairs or emergencies and at the same time insight will be gained into the structural life of the asset, allowing the teams to proactively plan ahead.

*Table 1, Observations from the field*

| | Description | Picture |
|---|---|---|
| 1 | On the landside localized shrimp ponds are present and clay excavations have taken place in the past. These ponds could trigger seepage and result in stability issues. Recommendation would be to fill these ponds with compacted soil. These ponds could be relocated away from the embankments. Clay cladding of bottom and slopes will prevent salt intrusion. |  |
| 2 | The slopes are steep, resulting in relatively high embankments. A thorough check on stability is required for every location, including transitions. The material of the dike does not seem to be well compacted and does not show erosion resistance. A check on micro-stability and its toe structure is important to ensure structural stability of these earthen embankments. |  |
| 3 | The stability of the landside slopes is at risk as a result of the steep embankments. This combined with the height of the embankment it is recommended to flatten the slopes and toe widen the footprint. For stability the construction of an earthen berm could be considered, realignment landwards could be needed. The increased footprint area of the embankment has be found behind in the hinderland. |  |

| | | |
|---|---|---|
| **4** | Grass revetment (well maintained and rooted) at slopes and crest will prevent the risk of erosion during overtopping. The current slopes are unprotected and could only deal with marginal quantities of overtopping water. In order to be structurally safe it is recommended to include a 20cm layer of topsoil plus deeply rooted, salt minding grass. |  |
| **5** | The structural stability and integrity of the floodwall on the crest is a crucial part of the structure of the embankment. The impact of dynamic loading and settlement needs to be considered in the design of the vertical structure. Settlement and consolidation of the earthen core needs to be limited to avoid gaps, resulting in erosion. |  |
| **6** | The material characteristics and the grade of compaction of core and slope materials is crucial for the strength and stability for the embankments and sea dikes. Moisture content, compaction, workability are crucial aspects during construction. Preventing large settlement and uncontrolled consolidation, therefore it is crucial to build well compacted, gradually layered/build dikes. |  |
| **7** | The applied blocks (including filter layers) need to be designed and placed to withstand wave action during cyclone events. Would a riprap revetment be more efficient? Special attention to the construction joints, the horizontal/vertical interfaces. Visual inspection is needed, cement cladding is not necessary. |  |
| **8** | The toe structure that needs to fixate the block placed revetments on the slopes needs to have the required stability/durability to counter the impact of erosion, scour, de-rooted mangrove trees and settlement of the structure. Durability of the material is important since replacement is expensive. Alternatives for steel sheetpile structures? |  |
| **9** | In those areas where the embankments are aligned close to the water, realignment is the sustainable way forward. In those areas where this cannot be achieved in the short term (next couple of years), intermediate measures should be implemented to prevent the foreshore from eroding. The porcupine structures are a proven 'intermediate' solution. |  |
| **10** | The end of the toe structure should be flexible, being able to adjust to changing foreshores. Examples of tetrapods have been seen. Interface between concrete and sand needs to be softened. Rocks on a filter structure can act as a fallon apron providing stability to the slopes, when scour, close to the toe occurs. Monitoring is needed. |  |

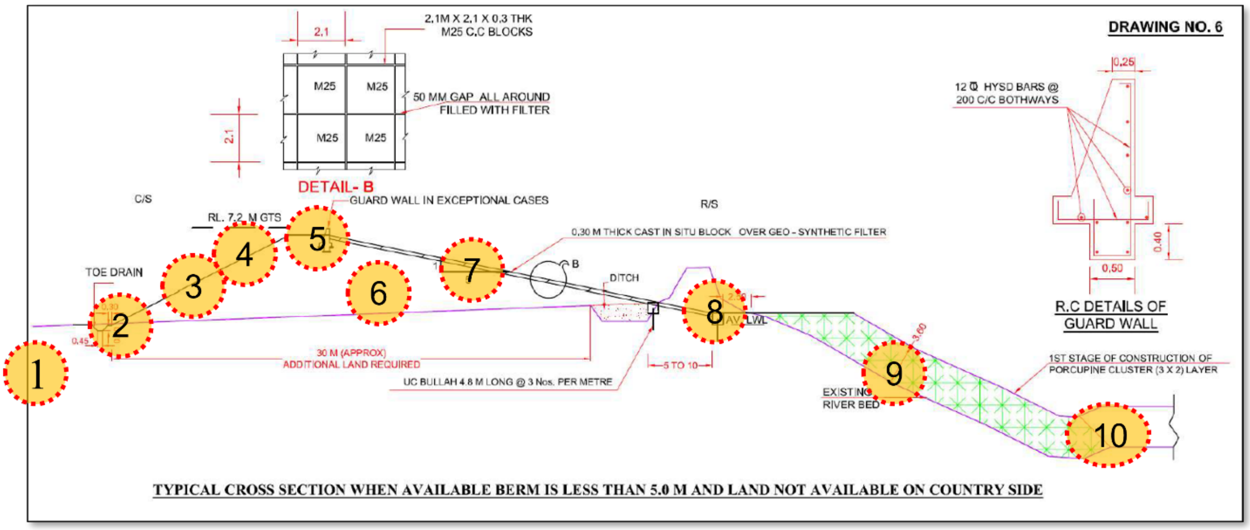



*Figure 2-4, Typical cross section*

Lessons learnt from the challenges encountered during the feasibility and design studies and the implementation phases of World Bank's Coastal Embankment Improvement Project in Bangladesh, seem to be useful and could be considered:

1. Clear understanding of the coastal system and dynamics is crucial for identification of the potential dynamics, erosion and accretion trends. Analysis of these aspects will result in definition of the vulnerable locations which necessitate either embankment retirement or in case the latter is not possible due to land acquisition issues, riverbank protection works. System understanding should be supported by morphological models, combined with a thorough assessment of satellite imagery analysis of riverbank movements and riverbank/ bathymetric survey data;
2. The polders under rehabilitation are subject to serious and frequent erosion, causing rapid reduction of set-back distances of the adjacent embankment. The alignment of the embankments requires to be selected prudently, taking into consideration the morpho-dynamics of the river and coastal systems;
3. It is advised to include bank protections at those locations in the selected areas where it is now urgently required and build in flexibility for those locations which may have to combat erosion during the implementation period of the project.
4. Land acquisition is a critical factor for the progress of the works. As a lesson learnt for the next phase a realistic work plan should be prepared taking into account the actual time required for getting access to the site;
5. Availability of materials like filling materials for embankments and filter layers was and is a challenge in the implementation. Alternatives have been found;
6. An important aspect of the design of the embankment is the required safety level which determines the embankment height, since it will potentially result in cost

reduction, limitation of land acquisition necessity and more flexible and sustainable solutions;
7. It is furthermore noted that the design of coastal interventions should follow a more adaptive approach which takes functional requirements, land use zoning and safety levels into account like e.g. is done in the Netherlands;
8. Grass turfing is a good option for slope protection, where wave action is negligible.
9. Regarding land acquisition and resettlement, it has been observed that the payment of compensation takes a very long time. More efficient ways and means for payment of compensation should be investigated and the project should allow time for this.
10. Revisiting of the operation & maintenance requirements is significant for the smooth performance of the works both during construction and the design life of the project.

### 2.2.4. Levee Design Process

The 1800 kilometres of embankments, sea dikes and structures suffered over 700 breaches in the most recent cyclone Amphan. Emergency response and repair activities have promptly been carried out. The key question is where to pro-actively start reinforcing the flood protection structures. It is recommended to prepare a strategy and implementation plan to bring all flood defence structures up to the required level of protection. This also needs to fit in with the wider strategy for the Sundarban, supporting the further development into a safe and sustainable environment for the area and its people. In order to organize and to prioritize the embankment and sea dike reconstruction work a close understanding is required on the hazards and the risks for the area. The process can be broken down in five steps.

1. Based on vulnerability mapping for the area, those flood protection structures most impacted by storm surges and cyclones can be identified. River and coastal stretches prone to erosion are relevant too. This mapping will highlight areas, stretches most at risk.
2. From a structural perspective for the embankments and sea dikes an inventory is required on their current condition. Which embankment and structures are up to standard, and which require maintenance or repair urgently? This is a massive catching up exercise for the Department of Irrigation and Waterways to do but is crucial in understanding the sort and number of weak spots.
3. Not all areas of the Sundarban require the same level of protection. Villages, people, livelihoods, farmlands need to be protected. Other areas, for example nature reserves or aquaculture fields are of a different order because impact of flooding is less. For example, do 500 meter no building zones require flood protection? A map outlining the differences will further guide the process of prioritization of high-risk areas.
4. Combining the cyclone hazards, the status and quality of the existing flood defence structures will point into the direction of weakest spots within the 1800 kilometres of embankments and sea dikes. Knowing the high-risk areas, the valuable and important sites will further assist in the categorization and prioritization of flood protection works.
5. All together in a strategic roadmap, presented over time for the next decade, will combine and present short-term fixes and long-term perspective for making the Sundarban a cyclone safe place to be. This roadmap is not cast in stone of course, it should periodically be updated based on new insights and understanding in the area.

The design process of an embankment, sea dike or protection structures as per the International Levee handbook is presented in Appendix 6. The design of an embankment or sea dike is a multidisciplinary exercise in which hydraulic, geomorphological, and geotechnical aspects are considered and balanced. This is not a stand-alone flowchart but should be read together with the other flowcharts in the manual. Nevertheless, it provides overview, order of sequence and key points of decision making by the designers to arrive at the preferred design solution.

The collection of data is crucial to understand the area, the river, other water courses and the embankment and to make informed decisions on design and layout moving forward. The process of data collection can be divided across different design phases of the project, building upon lessons learnt and gained insights. Examples of relevant items to be collected are morphological and hydraulic data on behaviour of rivers and coastlines (incl. scour), soil conditions, geotechnical data of existing embankments and sea dikes, geometry of flood defence structures including foreshore and hinterland survey/digital terrain models and for example current land use and future development plans. Table 9.2 from the International Levee Handbook provides an overview of a logical data process for each design stage.

Erosion threatens the structural integrity of embankments and dikes in the Sundarban. Many of these embankments are located close to the river and the erosion process gradually scrapes away the foreshore, essential for the overall stability of the embankment. Fixating these foreshores by placing porcupines provides a solution in the short term. The more sustainable solution would be to realign these stretches of embankment inland, ensuring sufficient foreshore, sufficient buffer area preventing instability of the structures. A vulnerability assessment will highlight these areas, a balanced approach needs to be found between realigning and interest of the people and their livelihoods on the inside. This requires a tailor-made approach and should be dealt with on a plot-by-plot level.

The basic design process, from the flowchart in Appendix 6, can be summarized in the following steps, referring to the different chapters from the International Levee Handbook:

1. What are the governing hydraulic boundary conditions (water levels, waves)?
2. Determination of flood protection standard. What is the alignment, crest level?
3. Initial sketch of preferred geometry, slope, berm, foreshore, hinterland, in line with chapter 9.5.
4. Check on geotechnical dike stability, macro (slope) stability, micro stability, piping in line with chapter 9.7 and 9.10.
5. Design of revetments (nature-based solutions, grass, concrete/rock), chapter 9.6.
6. Combination, variation with local environmental conditions.

In the geotechnical and structural design of the embankments the identification and selection of fill materials is important. These (earthworks) materials need to be selected, tested from potential borrow sources. Best structural performance, cost and environmental aspects need to be balanced. Clay material (and to a lesser extend the layer of topsoil supporting growth of well rooted grass desk) need to be the erosion-resistant layer (TAW, 1996). Therefore sand content (<40%), organic material (<5%) and salt content (<4%) should be within limits and mimimal treshold levels for its liquid limit (>45), plasticity index (>18) and water content (>0,6) are required because of its workability. Testing needs to be done at regular intervals, making sure that homogeneous quality of clay layer is achieved. The clay material should be free from debris, wood, logs, stumps, roots etc and of extreme colouring or smell. The technical requirements of the core material of the embankments can be less strict. A more sandy (>40%), clayey gravel type of material suffice, excluding peat, materials from swamps, marshes and bogs. For reason of settlement and consolidation the organic content should be limited and also the core material should be free from debris, wood, logs, stumps, roots etc.

The design of transitions is relevant, because reconstruction works will be phased over time, reference is made to chapter 9.11. Chapter 9.13 on the construction of levee earthworks is also relevant for this particular situation.

***Remark**: Following state of the art good international practices in adaptive dike designs will result in location specific safe and strong dikes when constructed. However, if in the final detailed design stage and preparation of the technical specifications and tender documents and actual construction compromises are made which deviate from the original design due to for example unavailability of specified materials, problems to fit the designed dike configuration due to problems in land ownership, will lead to sub-standard quality of a dike which will look nice on the outside but has many shortcomings hidden underneath its visible part and will not meet the required safety specifications and might fail already under lower extreme conditions. This will make the large investment futile.*

## 2.3. Delta morphodynamics

Erosion of coastal and estuarine embankments results from various mechanisms, some natural and some caused by human interventions. This section provides an overview of the type of erosion processes in both the tidal estuaries (such as the Matla, Raimangal) and coastlines facing the Bay of Bengal.

### 2.3.1. Erosion processes

A natural tidal estuary is typically composed of one or two deeper channels, intersecting shallow subtidal and intertidal flats, and is fringed by salt marshes (temperate regions) or mangroves (in the tropics). Tidal channels are by nature dynamic, with the main channel(s) migrating laterally. When one of such channels encroaches a river bank this (typically outer) bank erodes, compensated by sedimentation on the other (mostly inner) bank. Such erosion is cyclic, and may in some cases be prevented by strengthening the embankments. Many channels in the Sundarban experience this kind of erosion (Figure 2-5).

The Sundarban delta forms a complex tidal network with interconnecting tidal channels which is under natural conditions quite stable (Hoitink et al., 2017) but is very sensitive to human interventions (Fagherazzi, 2008). The large change in the channel network observed in Figure 1-3 clearly reveals an imbalance, and thereby the profound impact of human interventions, especially related to the very large amplitude of the tides. This means that the system at a large scale is changing, and since such changes are slow, they are probably still taking place. Large-scale changes (delta reorganization) feed back into morphologic changes on a lower level (e.g. lateral channel migration) which is therefore influenced by local, natural processes but also steered by slower, large-scale processes. Channel network reorganization may lead to abandonment of some channels (leading to infilling) and scouring of others (leading to bank erosion on both sides of the channels) – see Figure 2-5. Bank erosion resulting from channel reorganization may be more structural because the tidal volume is increasing, but also because the tidal range is increasing. It is therefore more difficult to mitigate and bank protection works need to be stronger compared to bank erosion due to lateral migration (as above).

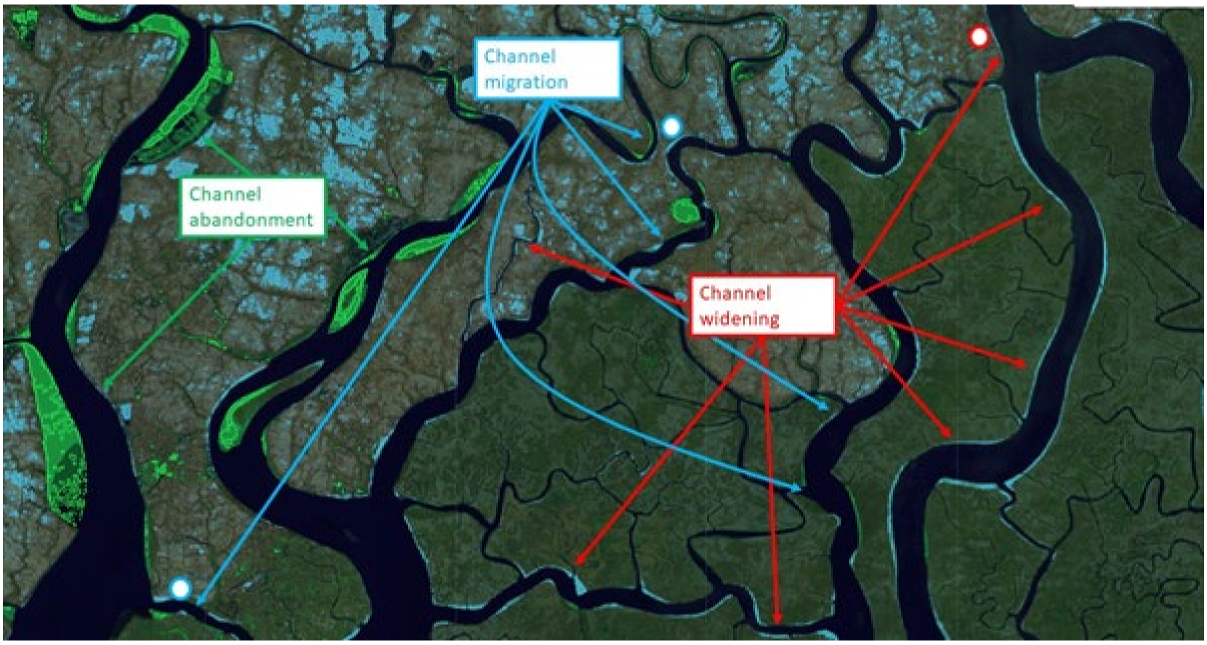



*Figure 2-5. Indicative channel dynamics based on the Aquamonitor ([www.aqua-monitor.appspot.com](http://www.aqua-monitor.appspot.com)) in the area visited from 17-20 April. Green areas / riverbanks indicate accretion between 1990 and 2020; blue areas indicate erosion (or in case of embanked areas: land that was dry in 1990 but was covered by stagnant water such as ponds in 2020. The arrows point to areas with channel abandonment (green), channel migration (blue) and channel widening (red). White circles denote location of site visits (with the edge colour indicating the type of erosion).*

The coastlines facing the Bay of Bengal suffer from erosion because wave-driven erosion processes (leading to coastal erosion) are not compensated by a sufficient sediment supply. This erosion is structural because the main sediment supply has migrated eastward (to the Meghna estuary), resulting in a coastal retreat of 12 km over the past 250 years (see also Figure 1-3), corresponding to 50 m/y. Erosion rates in the past decades can be monitored with satellite images ([https://aqua-monitor.appspot.com/?datasets=shoreline](https://aqua-monitor.appspot.com/?datasets=shoreline)). Such large erosion rates are still observed along the Sundarban shore facing the Bay of Bengal at Bulchery island, but most of the other Sundarban shores erode at 20 – 40 m/year. Embanked shorelines such at Sagar island erode more slowly, averaging 10-15 meter per year (Figure 2-6a). However, erosion is extremely constant in time (Figure 2-6b). Such constant erosion rates reflect structural erosion mechanisms, resulting from a sediment deficit. Coastline erosion as structural as the south shore of Sagar is very difficult to mitigate, because any embankment stabilizing the shore will lead to a gradual steepening of the shoreface until the embankment is undermined and fails. Protecting such coastlines therefore requires bank protection works extending many meters into the ground.

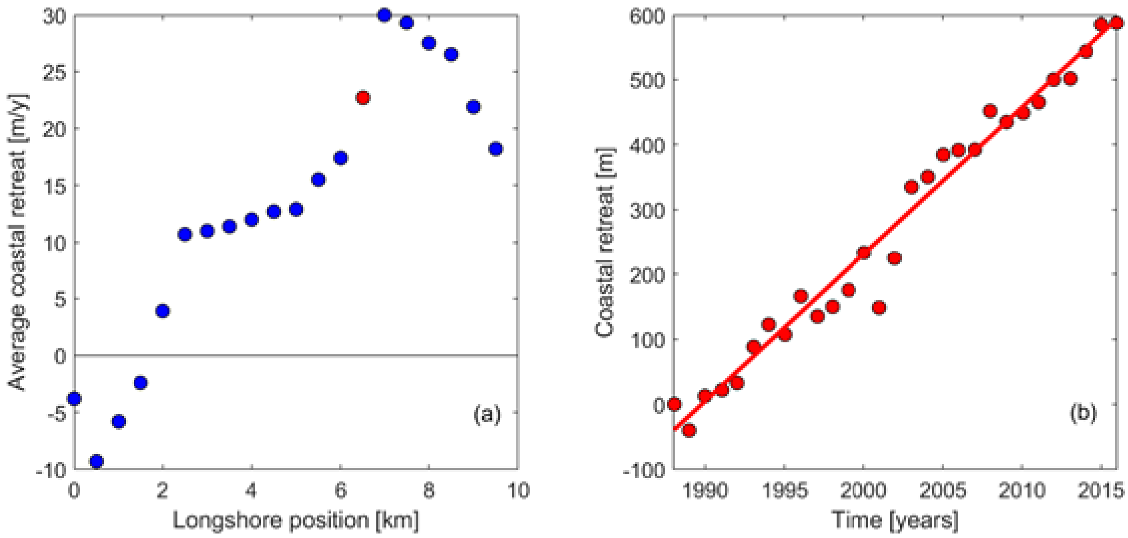



*Figure 2-6. Annual erosion rates along the south shore of Sagar island averaged over the period 1988 – 2016 (a), with the red dot depicting the location for which timeseries with cross-shore coastline retreat is provided in (b). From https://aqua-monitor.appspot.com/?datasets=shoreline.*

### 2.3.2. Understanding delta morphodynamics

The embankments are threatened directly by hydraulics (overflowing and breaching of the embankments and sea dike) as well as indirectly (erosion of the embankment / sea dike toe during tide-dominated conditions leading to failure during storms) there is a need to understand the hydrodynamics and its effect on the bed level in detail. This requires detailed monitoring of hydrodynamics (water levels, salinity) throughout the delta, and regular bathymetric surveys – see Appendix 5.

In parallel, and not waiting for newly collected data to become available, the system should be analysed with readily available information (satellite-based data as in Figure 2-5 and Figure 2-6, recent literature (Chatterjee et al., 2013) and historic reports often containing large amounts of data (Maitra, 1969; Chatterjee, 1989; references in Chatterjee et al., 2013)). Such analyses provide strong indications where embankments are under greatest threat. The flow velocities near threatened embankments should also be surveyed as soon as possible, since such observations provide strong indications whether the system is in equilibrium (moderate flow velocities) or expanding (much higher flow velocities, e.g. in excess of 2 m/s). Embankment improvements may start based on such considerations (i.e. areas at which the tide is amplifying, the channel widening, and flow velocities very high should be upgraded first). Such improvements may not necessarily be strengthening but may also be realignments – see following sections.

After monitoring is put in place, the data needs to be continuously analysed and embankments improved based on progressive new insights into the functioning of the delta. Especially repetitive bathymetric surveys will reveal how the channels are developing (infilling, expanding or migrating) which is crucial for maintenance of the embankments. With progressively more data being collected, the system can be progressively better understood and embankments upgraded accordingly (on the short, mid and long term).

Understanding the eroding mechanisms is essential for designing measures. The mechanism which is most difficult to mitigate is sediment shortage. For sites such as Sagar, embankments need to be extremely strong and even then may be insufficient to withstand erosion. Another site with erosion resulting from sediment shortage (Digha, see Annex 6) may benefit from sand nourishments (in contrast to Sagar, sand along the coastline of

Digha remains largely trapped). The most sustainable solution for Sagar is a sort of managed realignment (landward retreat of the primary sea dike). The preferred option for sites suffering from an imbalance between tidal volume and channel cross-section, resulting in channel widening, is managed realignment. The abandoned coastline should be strengthened with nature-based solutions in order to slow down erosion or even revert to sedimentation – see section 2.4. An alternative approach is to trap sediment, although this may require very strong hydraulic structures. When constructing a new embankment, the former embankment can remain in place to create a system of double dikes with a zone in between for sedimentation (see section 2.4). The default direction for mitigating measures for lateral migrating structures is a combination of embankment strengthening and sediment trapping (with porcupine groynes).

## 2.4. Nature-Based Solutions

The Sundarban Delta has a large potential for the implementation of Nature-Based Solutions (NBS). We identified two types of NBS that are largely applicable for the Sundarban area, which will contribute to a sustainable delta, both ecologically and environmentally. Below, we explain which types and why their potential is large. Subsequently, we indicate why implementation is now hampered and outline which steps need to be taken to implement the solutions for a sustainable Sundarban Delta.

(1) The main NBS for this area should focus on trapping sediment within the delta in the right places. These measures counterbalance sea-level rise and subsidence (see Ch. 1.4) and create a gradual transition from land to sea with a protective mangrove greenbelt, dampening waves and peak flow velocities along riverbanks. The Bay of Bengal provides a large stock of sediment allowing sediment trapping strategies to build and raise new land in the Sundarban Delta, at least on a decadal timescale – at longer timescales accelerated sea level rise may lead to sediment shortages.

(2) Local communities have shown resilience and adaptation, which largely enables socio-economic solutions that sustainably improve livelihoods. Examples are cascade aquaculture in saline zones and community involvement/empowerment in implementation of solutions and monitoring.

While the intention of ongoing initiatives around NBS is excellent (e.g., multi-layer vegetative shield, sustainable aquaculture), unfortunately, the current methodology for the implementation of Nature-Based Solutions has adverse effects. Examples of sub-optimal implementation of mangrove forests on inner river bends of already tight channels, where implementation may enhance erosion in the outer bend (e.g. p. 21 in NEWS, 2021) and the implementation of saline aquaculture in areas targeted for securing freshwater availability. Part of the problem may result from a focus on quantity (e.g., surface area realised) rather than quality and sustainable effects. Successful implementation of NBS will require a layered approach of design, implementation, monitoring, evaluation, and upscaling.

### 2.4.1. No regret changes in implementation of NBS

Protection of existing forest area and increase in total forest area is in principle a good idea (Annex IX in WB I&WD/PUM, 2022), but focus should be on quality and impact rather than on quantity of area implemented. Implementation should therefore be goal oriented (*why* and *where*). There should be a location specific reason to implement a solution (such as prevention of bank erosion), other than that the site conditions are favourable (sites where erosion problems typically do not occur). Such a goal-oriented approach automatically prevents adverse effects (for example implementing mangrove forests on inner river bends of already tight channels, where implementation may enhance erosion in the outer bend.

Implementation of NBS within is not advised in the wide tidal channels and coastlines exposed to waves from the Bay of Bengal. Those areas are too erosive for sediment trapping structures and implementation of mangrove greenbelts. Such areas should be prepared for managed realignment/retreat (relocating embankments inland). Which areas are too erosive needs to follow from site-specific studies, but a first order estimate is that channels should not be wider than 1000 meter.

When embankments or sea dikes are relocated inland by 100-500 m (see Ch. 2.2.3) and Annex IX in Van Meel, 2022) , opportunities arise for NBS. The old, retired dike can be kept in place, which can result in a double dike system with either space for sedimentation and growth of a protective mangrove greenbelt, or cascade aquaculture (see Figure 2-7, Tonneijck et al., 2016). Implementing NBS in combination with managed realignments will at least slow down erosion rates of the abandoned section, but may also set in motion processes which will in time revert erosive coastline stretches into accreting stretches and can contribute to dampening of the tide (Ch. 2.3).

*Figure 2-7: Example of a brackish water landscape with a cascade of aquaculture ponds, behind a mangrove greenbelt (from Tonneijck et al. 2016).*

### 2.4.2. Short-listing the right NBS for the Sundarban

This task results in a toolbox with the best applicable Nature-Based Solutions for the Sundarban Delta. The overview is composed based on a short review of ongoing initiatives in the Sundarban and is extended with examples of good practice from projects worldwide. Assessed measures will include sediment trapping (see Figure 2-8), rehabilitating mangrove belts, managing coastal retreat, restoring tidal dynamics and double dike systems. Per measure, the applicability for the Sundarban will be assessed, which results in a short-list of relevant measures to design and implement. Those measures can be used in the Masterplan for the Greater Sundarban Basin.

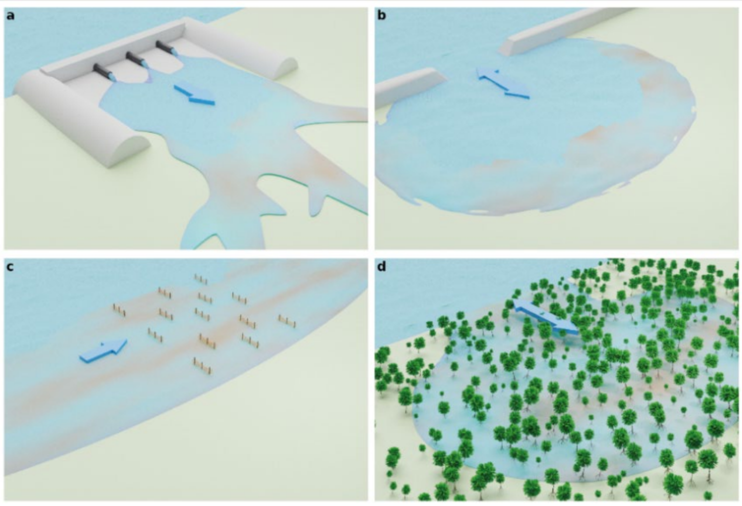



*Figure 2-8: Illustrations of four common types of NBS to trap sediment (Cox et al., 2022): (a) River sediment diversion, (b) tidal flooding, (c) sedimentation structures, and (d) sediment trapping vegetation. Arrows indicate flow direction.*

### 2.4.3. Improved implementation workflow NBS (incl. location selection)

Projects in the past have failed or resulted in adverse effects due to poor location selection. In this task the system analysis from Ch. 1.2 and 2.3 should be used to optimise location selection based on guidelines. This task therefore consists of two parts:

(1) The guidelines for implementation of NBS (e.g. in the Mangrove Manual, NEWS, 2021) should be updated and extended based on system characteristics. Emphasis should be placed on the (abiotic) conditions that are required for the specific NBS (e.g. a sufficiently high tidal flat) and the location in the delta system where those conditions can be realised (e.g. in a location where it can provide dampening for incoming wind-generated waves).

(2) Identification of potential locations for the short-listed NBS resulting from task 1.1. A combination of the guidelines along with the system analysis from Ch. 2.3 will provide sufficient information to select those locations: sites should be sufficiently energetic to be useful but not too energetic in order to be feasible.

### 2.4.4. Design and implementation of pilot projects

Based on the potential locations, it is suggested to design and implement pilot projects with NBS. One of the projects should focus on sediment trapping by means of porcupine groynes to strengthen coastal safety in the long-term in areas where this can strengthen coastal defence or reduce incoming waves on the embankment or sea dike. Once sufficient sediment has been trapped, mangroves will develop naturally, further protecting the coastline. Another project could focus on raising land by implementing a double dike system or a temporarily open polder. Sediment laden water can settle in the polder, which raises the land and over time may be put into productive use again. Continuous monitoring of those pilots is advised, for adaptive management and to answer questions such as: How rapid does the sedimentation occur? And therefore: how long do polders need to be open before land is raised sufficiently? And how long after the placement of porcupine groynes do vegetated foreshores emerge? The local community can be involved and empowered in the implementation and monitoring.

### 2.4.5. Upscaling of pilot projects based on system analysis

Based on lessons learnt from the pilots, and thorough system understanding following from the steps taken in Ch. 2.3, the NBS-approach can be upscaled in the Masterplan for the Greater Sundarban Basin (see Ch. 2.1).

## 2.5. Implementation arrangements

### 2.5.1. Institutional setting

The Sundarban Integrated Delta Development Project (SIDDP) falls under the jurisdiction of the Ministry of Jalshakti (MoJS) of the State Government of West Bengal, India. The State Line Department for the Project is the Irrigation & Waterways Department (I&WD) which is headed by the Principal Secretary Mr. P.K. Mishra (IAS). Day to day management of the I&WD falls under the responsibility of Secretary Mr. A. Roy. With respect to the technical planning, design, and implementation activities the Secretary is assisted by the Joint Secretary (Works) Mr. B. Mukherjee.

The I&WD has a Design Section which is responsible for all designs of irrigation and waterways infrastructure. The River Research Institute (RRI) is an affiliated institute responsible for hydrological and hydraulic research in support of the Department.

To assist in the integrated approach of delta development the I&WD will cooperate with the West Bengal Accelerated Development of Minor Irrigation Project (WBADMIP) which falls under Water Resources Investigation & Development Department (WRI&DD). The WBADMIP will mainly contribute to minor irrigation water management within the developed areas of the Sundarban aspects and community participation.

On Wednesday 20$^{th}$ of April 26, 2022 a Letter of Intent has been signed between the Irrigation and Waterways Department of the Government of West Bengal, India and The Embassy of the Kingdom of The Netherlands to India on co-operation in the field of Integrated Water Security for Sustainable Development of West Bengal Sundarban Delta and the coastal area of Digha. The parties have expressed to cooperate to take steps to pursue follow-up with the drafting of a two-year program for technical cooperation starting from April, 2022 based on the recommendations following from this DRR-mission.

### 2.5.2. Implementation arrangements

The Government of West Bengal intends to seek financial support through an International Financing Institute (IFI) for implementation of the SIDDP.

The project components are:
(i) Increased flood protection by creation of appropriate rehabilitation/rebuilding/new dikes and/or appropriate Nature-Based Solutions
(ii) Risk based Master Plan, prioritizing activities, based on both short-term needs and long-term goals.
(iii) Ensuring a freshwater environment within the developed areas by providing control sluices to avoid saline water intrusion and drainage of access water.
(iv) Rejuvenating rivers to provide for continuous flow from upstream part of the river system to reconnect it with the Sundarban delta by opening up former river branches or canals using "Room for the River" principals.
(v) Creation/Re-excavation of creeks to optimise rainfall harvesting for assured irrigation for agriculture, horticulture, fishery etc. and future clean economic activities
(vi) Ensuring freshwater availability for domestic needs.
(vii) Strengthening community-based institutions by active involvement of the community, smooth implementation of the project activities, ownership and better upkeep of the infrastructure created.

It is proposed to start the SIDDP with a Pilot phase of two to three years. This preparatory/pilot phase would entail:

(i) Preparation of a Master Plan
The Master Plan will cover the long-term planning for the entire river system from Calcutta to the Sundarban with the aim to rejuvenate the systems water dynamics and create healthy rivers and a connected dynamic delta. With respect to the SIDDP it will yield conceptual designs and specifications for different types of dikes and nature-based interventions as per international state of the art.
(ii) Data Collection & Monitoring
Development of a monitoring strategy and implementation of a monitoring network. For proper planning and execution this is a prerequisite.
(iii) Planning, Design & Execution of a Pilot Project
(iv) International Technical Assistance

The Pilot Phase will be followed by the full implementation of the dike, nature-based solutions and sluice construction to create the required freshwater environment and safeguard natural delta dynamics. Based on the lessons learnt during the pilot phase it will include detailed planning and scientifically based designs and state of the art specifications and tender documents, supervision with strict quality control and subsequent monitoring. With a total length of 540 kilometres of dikes to be rehabilitated/reconstructed/newly built the first implementation Phase aims in completing 175 kilometres of the total length consisting of various types such sea-dikes and river embankments upstream.

To provide meta guidance to project implementation from an administrative as well as from a technical planning and design objective a SIDDP Steering Committee is proposed to consist of Senior Administrators and Technical Experts from WB complemented by international Experts from the involved IFI and International (Dutch) Experts on integrated planning and design of deltas.

Within the context of the West Bengal – The Netherlands Cooperation on Integrated Water Security for Sustainable Development of West Bengal Sundarban Delta and coastal area Digha it is proposed to continue and expand the bilateral cooperation with the following activities:

(i) Facilitating a collaboration of a Dutch university of repute with the River Research Institute (RRI) under the Irrigation and Waterways Department
(ii) Specific technical missions on capacity building on:
    a. upgrading dike design
    b. hydrological and morphological investigations and implementation of a monitoring strategy in the Sundarban Delta
    c. practical approaches for nature-based solutions to strengthen flood protection, grow with sea-level rise and improving delta dynamics
(iii) General Technical Assistance (TA), strategic advice on master planning and integrated delta management

### 2.5.3. Pilot project

Before large-scale implementation of novel concepts for integrated delta development and management in the Sundarban delta, it is highly recommended to start with application on a smaller scale. It is therefore proposed to plan for the design and implementation of a pilot project located at a representative location in the Sundarbans. For the purpose of this report the Satjelia Island has been selected as a potential location.

The aim of the pilot is to realise a safe freshwater environment within the polder to allow for sustained and improved water management. This will be realized by location-specific design and construction of embankments and design and construction of control sluice(s) at the mouth of the major creek intersecting the island, Satjelia Khal.

The concept of the creation of a safe and sustained freshwater polder on Satjelia Island is shown in Figure 2-9. It is self-explanatory with respect to protection by embankments (for safety and preventing inflow of salt water during storm conditions) and sluice structure(s) (to allow for drainage of excess water in the monsoon period whilst preventing saltwater intrusion and preventing fresh water to flow out during the dry period). Rainfall is collected in existing creeks as well as in relict creeks that have been deepened specifically to provide extra volume for rainfall collection (Water Detention Structures). The minor irrigation infrastructure will need to be remodelled to provide for improved drainage where smaller creeks have been cut off.

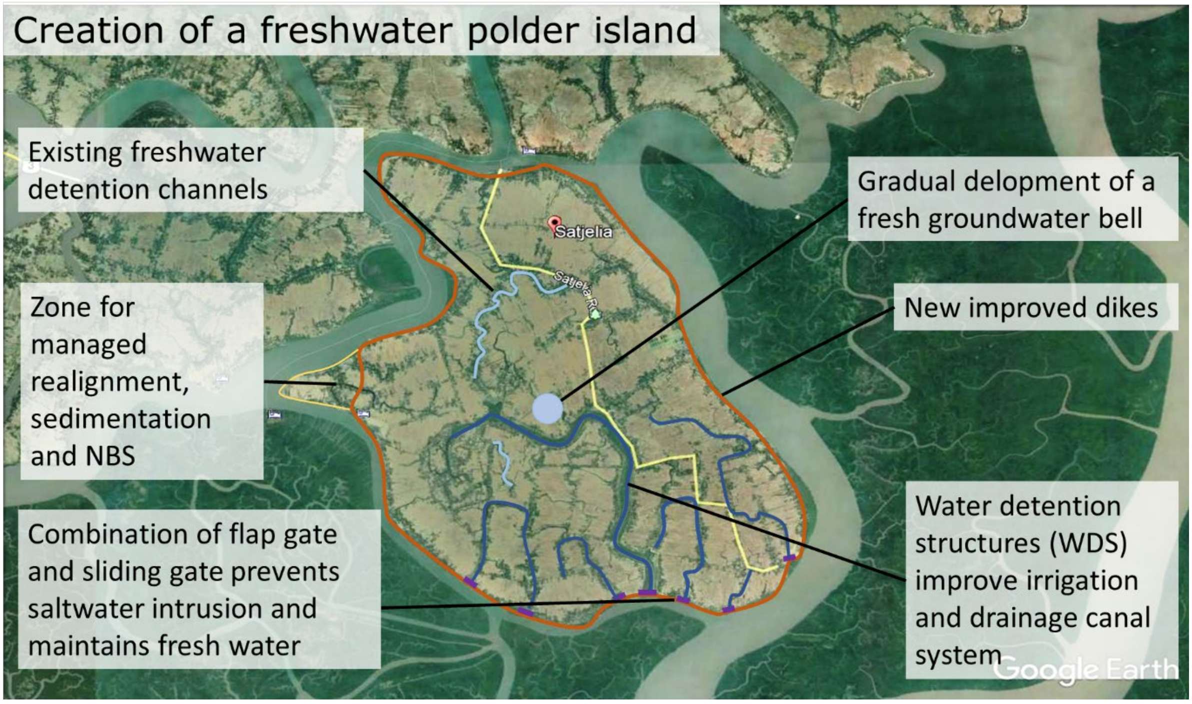



*Figure 2-9: Conceptual figure outlining the potential of a pilot on Satjelia Island.*

There are three potential sources of water for agriculture in de Sundarban Delta: (1) rain water that is collected during the monsoon/rainy-season, (2) shallow groundwater, (3) deep groundwater. Because the shallow groundwater is often saline, deep tube wells of approximately 300 metres deep are drilled to reach a freshwater aquifer. Unfortunately, the approach with deep tube wells is unsustainable in the long-term because there are already signs that the deep groundwater aquifer becomes depleted. People already experience deep tube-wells for drinking water becoming saline. Moreover, groundwater extraction increases subsidence with risks for future water safety. In creating a freshwater environment on the island also the groundwater will eventually become fresh and will create a freshwater bell floating on the deeper saline water. The thus created fresh water sources will be beneficial for domestic use.

Apart from the constructional design criteria the two hydro-morphological phenomena are import factors in developing realistic design criteria for the dike to be built.

- The design water level, required crest level, will be different per location both with respect to extreme high tide levels as attack of the embankments by cyclone wave surges. The latter depends amongst others on the depth of the foreland and the length of the free water in front which determines the wave built up.
- Delta dynamics of erosion and accretion also determine the to be adopted design criteria for the outer part of the embankment construction. In case of erosion a stronger design will be needed whilst in locations where accretion occurs consideration can be given to nature-based solutions. Especially in a first design phase satellite images (such as in Figure 2-10) reveal riverbank erosion and accretion around Satjelia Island, which can be used to optimize the location of embankment construction.
  As an example, the most western point of the island shows erosion (blue coloured on Figure 2-10 and also see Figure 2-9). One can try to fight this by building ever stronger (expensive) embankments. The location will probably remain under attack and continued maintenance of the dike may be required. It should be considered to adopt the strategy of 'managed realignment' of the embankment. In the short run

it will require expropriation cost but in the long run it may be the more appropriate economic solution. To head off further erosion for as long as possible the land in front of the dike on the river side could be made naturally stable by for example mangrove plantation.

In the southwest the river embankment shows accretion (green on Figure 2-10). At this location dike design could incorporate nature-based solutions by for example stimulate growing of mangroves and environmentally friendly aqua culture.

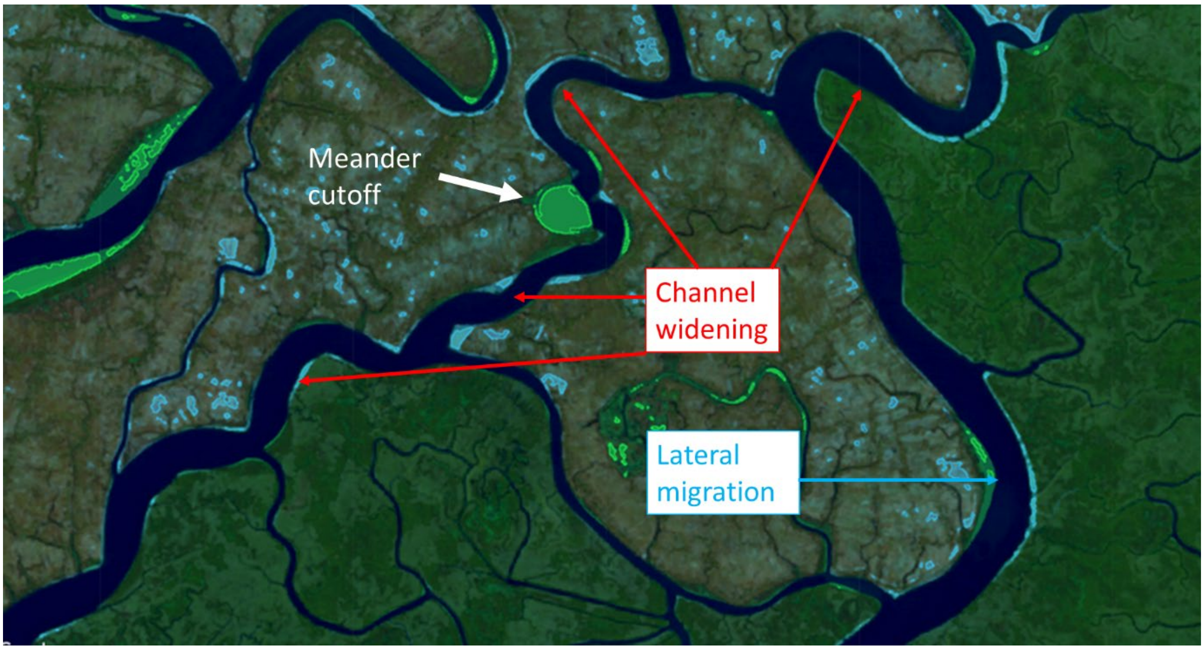



*Figure 2-10: Accretion (green) and erosion (blue) around Satjelia Island*

# 3. Roadmap

## 3. ROADMAP MOVING FORWARD

Key to the development of the Sundarban is to ensure water security by developing resilience against floods, the creation of a freshwater environment on the islands and restoration of fresh water to the Sundarban delta. The following roadmap provides the overview of recommendations on short-, mid- and long-term activities.

*Table 2: Proposed roadmap [NR = No Regret (Immediate/now), ST = Short term (0-2 years), MT = Medium term (5-10 years), LT = Long term (10-25 years)]*

| | What? | Chapter | By whom? | NR | ST | MT | LT |
|---|---|---|---|---|---|---|---|
| 1 | Masterplan for the Greater Sundarban Basin | 2.1-2.5 | I&WD i.c.w. relevant sectoral ministeries, departments | ✓ | | | |
| 2 | Adaptive Delta Management Plan for Sundarban Delta | 2.1-2.5 | I&WD i.c.w. relevant sectoral ministeries, departments | ✓ | | | |
| 3 | No regret adaptation in current practice for Flood Resilience | 2.2 | I&WD | ✓ | | | |
| 4 | No regret adaptation in current practice for NBS | 2.4 | I&WD, DoE, DoF, NGO's | ✓ | | | |
| 5 | Data collection, and planning of monitoring program | 2.2-2.3, App. 4 | I&WD | ✓ | | | |
| 6 | Risk based vulnerability assessment | 2.2 | I&WD | ✓ | | | |
| 7 | Conceptual design of embankments | 2.2 | I&WD | ✓ | | | |
| 8 | Short-listing the right NBS for the Sundarban | 2.4 | I&WD, DoE, DoF | ✓ | | | |
| 9 | Operation and Maintenance plan | 2.2 | I&WD, WRI&DD | ✓ | ✓ | | |
| 10 | Design and implementation of an integrated pilot to create water security | 2.5 | I&WD with WRI&DD / WBADMI Project | | ✓ | | |
| 11 | Improve implementation workflow and carry out location selection crucial for NBS | 2.4 | I&WD, DoE, DoF | | ✓ | | |
| 12 | Environmental and Social Safeguards | 1.5, 2.1 & 2.2 | I&WD with WRI&DD and responsible ministeries, departments | | ✓ | | |
| 13 | Conducting monitoring and continuously analyse delta morphodynamics | 2.3, App. 4 | I&WD | | ✓ | ✓ | ✓ |
| 14 | Detailed design and construction | 2.2 | I&WD | | | ✓ | |
| 15 | Model based predictions for delta hydrodynamics | 2.2 | I&WD | | | ✓ | ✓ |
| 16 | Upscaling of pilot projects based on system analysis | 2.5 | I&WD, WRI&DD, DoE, DoF | | | ✓ | ✓ |
| 17 | Capacity building based on lessons learnt | 2.5 | All above | ✓ | ✓ | ✓ | ✓ |

## REFERENCES


Bandyopadhyay, S., Mukherjee, D., & Pahari, D. (2009). Coastal erosion and its management at Digha, Medinipur, West Bengal. Geomorphology in India, 124-132.

Batholomew, J.G. (1893). 1:450000 Map of Calcutta and environs. Plate 37. Westminster: Archibald Constable & Company, MDCCCXCIII. Retrieved from DavidRumsey.com.

Bloemen, P., Hammer, F., Van der Vlist, M.J., Grinwis, P., & Van Alphen J. (2019). DMDU into practice: Adaptive Delta Management in The Netherlands. Chapter 14 in: Marchau, V., Walker, W., Bloemen, P., and Popper, S. (eds.) Decision Making under Deep Uncertainty – from Theory to Practice. New York: Springer.

Brown, S., & Nicholls, R. J. (2015). Subsidence and human influences in mega deltas: the case of the Ganges–Brahmaputra–Meghna. Science of the Total Environment, 527, 362-374.

Chatterjee, S.N. (1989). River systems of west Bengal. Report of the River Research Institute, Government of West Bengal.

Chatterjee, M., Shankar, D., Sen, G. K., Sanyal, P., Sundar, D., Michael, G. S., ... & Sarkar, K. (2013). Tidal variations in the Sundarban estuarine system, India. Journal of Earth System Science, 122(4), 899-933.

Cox, J.R., Paauw, M., Nienhuis, J.H., Dunn, F.E., van der Deijl, E., Esposito, C., Goichot, M., Leuven, J.R., van Maren, D.S., Middelkoop, H. and Naffaa, S. (2022). A global synthesis of the effectiveness of sedimentation-enhancing strategies for river deltas and estuaries. Global and Planetary Change, p.103796.

EC (2021). Protection of Coastal Areas and Earthen Embankment Through Vegetative Solutions. Report of the Expert Committee, Environment Department of West Bengal.

Eckland, A., Overeem, I., Diermanse, F., Giardino, A., Dunn, F. E., & Kamal, F. (2020). Modeling the Recent and Future Water and Sediment Discharge Regime of the Ganges-Brahmaputra Delta in Response to a Changing Climate. In AGU Fall Meeting Abstracts (Vol. 2020, pp. EP047-0013).

Fagherazzi, S. (2008). Self-organization of tidal deltas. Proc. Natl Acad. Sci. USA 105, 18692–18695, 2008.

Hoitink, A.J.F., Wang, Z.B., Vermeulen, Y. Huismans and K. Kästner (2017). Tidal controls on river delta morphology. Nature Geosci 10, 637–645 (2017). https://doi.org/10.1038/ngeo3000

IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. H.O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P.Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.).

IWD (2021). Report of the Committee of Technical Experts (CTE) on Sustainable Reconstruction of Sundarban Embankments damaged by the Extremely Severe Cyclonic Storm AMPHAN". Irrigation & Waterways Department GoWB

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., and Wu, L. (2020). Tropical cyclones and climate change assessment. Part II: Projected Response to Anthropogenic Warming, Vol. 101, Issue 3, https://doi.org/10.1175/BAMS-D-18-0194.1

Knutson, T.R., Chung, M.V., Vecchi, G., Sun, J., Hsieh, T.-L., Smith, A.J.P. (2021). Climate change is probably increasing the intensity of tropical cyclones. Science Brief Review. In: Critical Issues in Climate Change Science, edited by: Corine Le Quéré, Peter Liss, Piers Forster.

Laurie, R. and Whittle, J. (1804). 1:750000 Map of Bengal, Bahar &c. (south). Laurie & Whittle Publishers. Retrieved from DavidRumsey.com.

Leijnse, T. W. B., Giardino, A., Nederhoff, K., & Caires, S. (2021). Generating reliable estimates of tropical cyclone induced coastal hazards along the Bay of Bengal for current and future climates using synthetic tracks. Natural Hazards and Earth System Sciences Discussions, 1-40.

Maitra (1969). River systems of west Bengal. Report of the River Research Institute, Government of West Bengal.

Nature Environment & Wildlife Society (NEWS) (2021), Mangrove Manual in the context of Indian Sundarban Ecosystem.

Nishat, B., AJM Zobaidur Rahman, Sakib Mahmud (2019). Landscape Narrative of the Sundarban: Towards Collaborative Management by Bangladesh and India. IWM report prepared for the World Bank.

Survey of India (1930). 1:253440 Map of Bengal & Chandernagore, No 79 B, Calcutta. Retrieved from DavidRumsey.com.

Technical Report Clay for dikes, Technische Adviescommissie voor de Waterkeringen (1996)

Tonneijck, M., Halsema, G. van, Fiselier, J., Dirks. F. (2016). Mekong Delta Integrated Climate Resilience and Sustainable Livelihoods Project - Review Dutch Team on alignment with Mekong Delta Plan Framework; MARD components 2, 3 and 4 An Giang, Kiên Giang, Bến Tre, Trà Vinh. RVO-WB Review BE1936.

van Maren, D.S. J.G.W. Beemster, Z.B. Wang, Z.H. Khan, R.A Schrijvershof, A.J.F. Hoitink (submitted). Tidal amplification and river capture in response to asynchronous land reclamation in the Ganges-Brahmaputra delta. Catena.

Sánchez-Triana, E., Paul, T., Ortolano, L., and Ruitenebeek, J. (2014). Building Resilience for Sustainable Development of the Sundarban through Estuary Management, Poverty Reduction, and Biodiversity Conservation. International Bank for Reconstruction and Development / World Bank, https://openknowledge.worldbank.org/bitstream/handle/10986/20116/880610REVISED00ns000Strategy0Report.pdf?sequence=1

West Bengal Irrigation and Waterways Department and PUM (WB I&WD/PUM) (2022). Sundarban Integrated Delta Development, Draft Concept Note 8th March 2022.

## Annex 1 DRR-Team mission

### Team members

We DRR-team mission consists of four experts (see Table below) in order to fully cover the expertise required from dike engineering, delta morphology, integrated water resources management and nature-based solutions within the context of water resilience and climate change in the Sundarban Delta.

| | |
|---|---|
| Team Leader - Flood Mitigation / Dike expert | George Peters M.Sc. CE |
| Senior Delta Morphologist | Prof. Dr. Bas van Maren |
| Specialist Nature-based solutions / coastal morpho-dynamics | Dr. Jasper Leuven |
| Senior Strategic Advisor Integrated Water Resources Management | Paul van Meel M.Sc. CE |

### Planning of the mission & local contacts

The table below contains the followed program/itinerary for the DRR-team mission 'Sundarban Delta and Digha Flood Mitigation (and Coastal Protection)'. The mission took place over de period 16 – 28 April 2022. The column on the right lists all the involved contacts (e.g. with whom the team interacted).

| Date | Activity | Involved counterparts/ stakeholders |
|---|---|---|
| Sat 16 April | Travel from Amsterdam to Kolkata | |
| Sun 17 April | Early morning arrival Kolkata<br><br>First introductory meeting with the counterparts (Irrigation and Waterways Department of the Government of West Bengal)<br><br>Departure Field trip:<br>• Departure from Kolkata at 11.00 AM<br>• Reach Dhamakhali at 12.45 PM<br>• Start for Kumirmari through Launch and Lunch on the way<br>• Reach Kumirmari (Sukrobarer Bazar) at 02.45 PM leave the Launch<br>• Visit to Pathorkhali Sluice gate, Raimangal new embankment, Meeting with WUA (WRIDD), Palmari sluice gate<br>• Start from Rakhalmari Jettyghat to Dulki by Launch 6.00 PM<br>• Reaching Dulki around 8.00 PM<br>• Night stay at Sonar Bangla Hotel & anchor at Dulki | Principal Secretary Mr. Prabhat Mishra<br>Secretary Mr. Amit Roy<br>Officials from the Irrigation and Waterways Department and relevant senior representatives WRI&DD and Design Institute Irrigation & Waterways (DII&W)<br>Program Director & Joint Secretary Ajanta Dey from the Nature Environment & Wildlife Society (NEWS)<br>Mr. Joost Geijer (Head economic affairs, Embassy) |

| | | |
|---|---|---|
| Mon 18 April | Continuation of the Field trip in the Sundarban: assessment dike constructions, failures, execution issues, etc. Technical field discussions with experts WRI&DD and DII&W - Short workshops/trainings local engineers responsible for implementation. Workshops on building with nature initiatives (representatives Nature Environment &Wildlife Society (NEWS) and opportunities. Full program:<br>• Start from Dulki at 8.00 AM for Pakhiralaya by Launch<br>• From 8.30 AM Fragile embankment at Pakhiralaya facing river Gomor<br>• From 9.30 AM inspect embankment at Rangabelia facing river Bidya & Gomor<br>• From 10.30 Sudhanayakhali Reserve Forest enroute and continue for Jharkhali<br>• Reach Jharkhali around 3 PM<br>• Visit embankments near Jharkhali facing river Bidya (I&W Dte.) and visit to Tiger rescue center till 5.30 PM<br>• Night stay at Jharkhali Royal Sundarban & anchor | Chief Engineer Irrigation and Waterways Department and Experts Water Resources Investigations & Development Department (WRI&DD), DII&W, including Sundarban based Executive Engineers and staff. Workshops with local engineers, responsible for implementation.<br>Mr. Joost Geijer (Head economic affairs, Embassy) |
| Tue 19 April | Field trip continued and return to Kolkata<br>• Leave Jharkhali at 07.00 AM and start for Deulbari – Debipur by Launch<br>• Reach Deulbari – Debipur at 08.30 AM and inspect embankment facing river Matla( I & W Dte.) On the way<br>• Leave Deulbari – Debipur at 09.00 AM for inspecting embankment at Kishorimohanpur facing river Thakuran (I&W Dte.).<br>• Reach Kishorimohanpur at 12.00 noon and inspect site (I&W Dte.).<br>• Leave for Kolkata at 01.00 PM by road<br>• Reach ITC Sonar Bangla by 4.00 PM<br><br>Meeting with the Dutch delegation for the Bengal Global Business Summit 2022, including the Dutch ambassador. | See above<br><br>Dutch Ambassador in India: Mr. Marten van den Berg |
| Wed 20 April | Internal review by team of findings and start with the report writing<br><br>Attendance at the Bengal Global Business Summit 2022 (International Business Synergy Sessions) and assistence in business development for the Netherlands<br><br>Presentation about the DRR-mission in the Netherlands Country Session | Principal Secretary Mr. Prabhat Mishra Secretary<br>Dutch Ambassador in India: Mr. Marten van den Berg<br>Mr. Michiel van Erkel (agricultural counsellor, Embassy)<br>Mr. Arnoud Besseling (Finance Investment Agengy) |

| | | |
|---|---|---|
| | Progress meeting and contact about the content of our reporting in the evening with Mr. Prabhat Mishra. | |
| Thu 21 April | Internal review by team of findings / writing<br><br>Meeting with Dr. Bibhas Chandra Barman (Deputy Director/ River Research Institute) to discuss (historic) system changes in the Sundarban system.<br><br>Phone contact with Mr. Prabhat Mishra. | Dr. Bibhas Chandra Barman (Deputy Director/ River Research Institute)<br><br>Principal Secretary Mr. Prabhat Mishra Secretary |
| Fri 22 April | Report writing and meetings with<br>• Dr. B.B. Neogi: an experienced structural engineer who shares his past experience of working in West Bengal<br>• Dr. Kalyan Rudra: Chairman at the West Bengal Pollution Control Board (Department of Environment, Gov. of West-Bengal)<br>Mr. Prabhat Mishra also attended the meeting. | |
| Sat 23 April | Report writing and presentation of first findings by Dutch Expert Team and Workshop/Training at Kolkata for selected engineering staff | Experts Irrigation and Waterways Dept. and affiliated sub-departments and institutes ie River Research Institute.<br>Selected staff and guests Irrigation and Waterways Dept. |
| Sun 24 April | Sunday morning off-time. Departure to Digha (on the right bank of Hooghly River) and overnight stay in Digha. Presentation | |
| Mon 25 April | Field trip to Digha on right bank of Hooghly River with a coastal protection issue and part of the Sundarban Delta.<br><br>See for full details of the Digha field trip Annex 5.<br><br>During the field trip we connected the engineers from the Gov. of Odisha with the Gov. of West Bengal. They exchanged contact details for future contact.<br><br>Assistance in writing a Preliminary Project Proposal Report (PPPR) as a basis for an ADB fund request. | Chief Engineer Irrigation and Waterways Department and Experts WRI&DD, DII&W, including Sundarban based Executive Engineers and staff.<br>Engineers from Gov. of Odisha. |
| Tue 26 April | Writing and finalising the report. | |
| Wed 27 April | Discussion of the report and findings with Mr. Prabhat Mishra. Meeting with the ADB on potential funding of future activities.<br><br>Departure from Kolkata to Amsterdam | Asian Development Bank (ADB) |

## Annex 2 Terms of Reference

DRR-Team received a request from the Government of West Bengal (Department of Irrigation and Waterways) through the Netherlands Embassy in India, for support on flood risk management of the Sundarban. Due to the meteorological changes and the sea level rise due to global warming, there have been coastal erosions and breaches in the embankments in Sundarban. The area has faced mass scale devastation due to repeated cyclones in the past. The area also suffers from high level of salinity due to tidal rivers which has an adverse impact on agriculture and related livelihood opportunities. As a result, people in Sundarban live in a high state of vulnerability. In this context, there have been several interventions by Government of West Bengal to strengthen the embankments and stop saline water ingress. However, the designs of the sea dikes are not able to withstand this. The Government of West Bengal recognizes this, and therefore asked for the support of Dutch experts to cooperate with their Government in the design of sea dikes and embankment design, aiming at correcting the most urgent design and implementation errors.

The aim of the DRR-Team deployment is, together with the design engineers of the West Bangal Irrigation & Waterways Department, to examine the situation, and to provide advice on what can be done in the short term, and which measures can be taken in the longer term. The Department of Irrigation and Waterways previously collaborated with PUM and has actually implemented the advice in the field of rainwater harvesting.

The expert team should consist of an expert in the field of sea dike design and implementation, a coastal protection expert with knowledge of delta morphological processes and an IWRM expert with knowledge of the Sundarban Delta and integrated planning for water resilience and safety of delta areas. The experts should have affinity and experience with eco-engineering/building with nature.

### Scope and objectives

The West Bengal government is seeking assistance from Dutch experts in the technical implementation of dike rehabilitation and dike design according to international standards. At the moment, dike repair is taking place, but not with the right effort. A short advisory mission is needed, together with the design engineers of the West Bengal government (Irrigation & Waterways department), to correct the most pressing design and implementation errors.

The DRR-Team will prepare a report for the local government, with recommendations regarding the next steps to be taken (for the short, medium and longer term). All specifics of the deliverables are described in the full ToR.

## Annex 3 Dutch contact details

For more information kindly contact

Netherlands Enterprise Agency (RVO), DRR-Team programme, email drr-team@rvo.nl

Project Officer Mrs. F. van der Velde,
email Fernanda.vandervelde@rvo.nl, +31 6 11736553

## Annex 4 Monitoring campaign

The purpose of a monitoring programme is to (1) provide input for an Early Warning System and (2) collect data which can be used to better understand and predict the hydrodynamics and morphological changes of the monitored system

### 1 Early Warning System

An early warning system is a computer-based system which warns whether flooding is likely to occur. Such systems may be based on model predictions, on data, or on both. For a complex, poorly understood system such as the Sundarban a data-based approach is preferred. This requires continuous monitoring of water levels (see next section for more details) which are transferred automatically sent to a centralized location (telemetry).

### 2 System understanding

System understanding is the analysis of multiple aspects of the delta as a whole, accounting for interaction at various levels, in order to understand and predict its behaviour. This system understanding relates to bank erosion, but also fresh water availability. System understanding is build on generic knowledge, data, and numerical models (when available). The monitoring campaign fills in the data needs for this system understanding.

*Water levels*

Understanding bank erosion, but especially predicting bank erosion, requires a thorough understanding of the tidal propagation per primary estuary. The tides amplify in the landward direction, and relative differences in amplification between estuaries drives cross-channel flows responsible for erosion in some of the channels. Understanding this behaviour requires around 4 water level observation stations per major estuary (but preferably more), i.e. around 20 water level observations.

Long records of tidal observations provide strong indications for changes in the system (amplifying or damping of the tide in time; changes in the reference levels). The water level monitoring stations should be placed in such a way, that they ore robust (i.e. not damaged during cyclones) and not influenced by wave motions (i.e. in a sheltered environment). An aspect to account for in the Sundarban delta is subsidence. A water level observation point not fixed on a solid subsoil will lower in time. This may be beneficial because (1) it provides data on subsidence in the adjacent area) and (2) the area also suffers from tectonic subsidence anyhow which cannot be prevented. But which option is taken should be carefully considered and then uniformly implemented.

*Bathymetric data*

A second type of data, crucial for understanding bank erosion, is bathymetric data collected at regularly recurring intervals. A detailed bathymetric map provides valuable information on subsurface topography. This data can be input for risk assessment of dikes because a deep channel encroaching on an embankment means that the embankment is under great stress. The bathymetric data becomes even more valuable when it is repeated in time (every 5 to 10 years) because this gives insight in channel dynamics (i.e. the speed at which a tidal channel deepens or migrates towards an embankment). The bathymetry can be measured in several ways, using dual frequency echo sounders, multibeam echosounders and single beam echosounders. The advantage of the first is that it provides a seismogram for the subsoil, the advantage of the second is that it provides a large spatial coverage including bedforms (which may in time become important for system understanding), while the third option is the cheapest. An important point of attention measuring the bathymetry is the vertical referencing of the data. An echosounder with a fully automated pitch and roll corrected DGPS may instantly measure the absolute bed level, but a less sophisticated echosounder with only a horizontal position from DGPS requires correction for tidal levels in order to measure the absolute bed level.

*Flow velocity*

A third type of data is velocity. In tidal environments a velocity observation is often meaningless unless observations exist throughout the tidal cycle (requiring 13-hour flow velocity observations). Flow velocity data is relevant for the following aspects:

- It further charachterises the tidal dynamics (degree and type of tidal asymmetry, maximum flow velocities)
- It reveals the presence of residual flows / discharges. In a channel network such as the Sundarban residual flows may exist in which some channels preferentially transport flood waters whereas other transport ebb waters.
- It may be used to quantify the flow velocity near threatened embankments. The flow velocity provides an indication to what extent the channel bed is in equilibrium – excessively large tidal flow velocities suggest the channel bed is eroding.

The most commonly used methodology to measure flow velocities is an ADCP.

*Salinity*

The salinity is important for freshwater availability. It is therefore especially relevant in the regions with low salinity (<5 ppt) and measurements of salinity could concentrate on the upper parts of the tidal river (where the salinity is lower). The preferred option would be to measure salinity at the same location of the water levels.

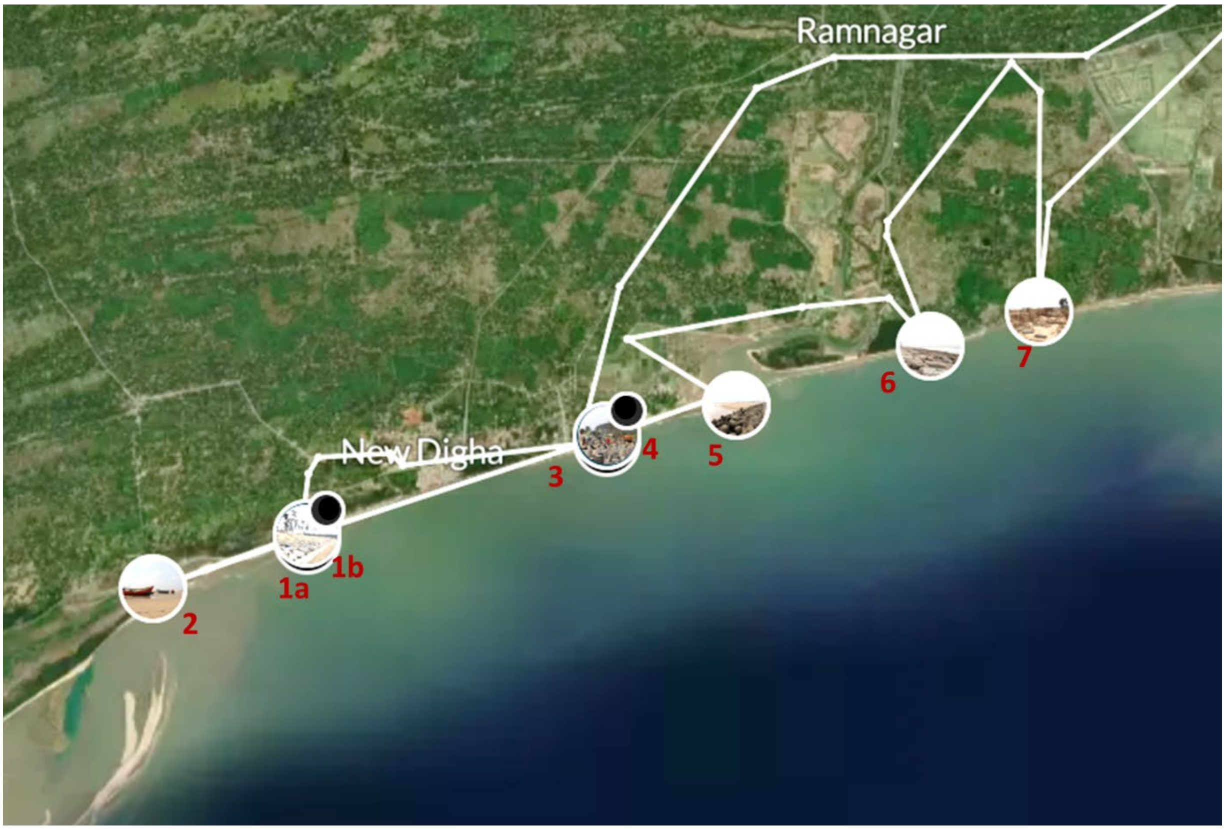
*Sediment distribution*

Full understanding of the Sundarban tidal network requires a the collection and analysis of bed samples collected in the Sundarban area. The higher the resolution of the collected bed samples the better, but approximately 20 samples per estuary already provide a reasonable insight into the bed sediment distribution. The bed samples should be analysed on the following aspects:

- Granulometry (distribution of sand, mud, clay). For detecting finer particles (clay) the methodology as well as the pre-treatment in the lab is very important. The analysis methodology should be carefully planned upfront, preferably aligning with existing quality control procedures, but making sure the aims of the analysis align with the quality control procedures (for instance, a fresh water muddy sediment samples requires different treatment than a freshwater muddy sediment samples).
- Density. Some parts of the Sundarban delta are erosive, others are depositional. The dry density of the bed material provides an indication for its state of consolidation, and thereby whether the sediment was recently deposited or eroded.

**Annex 5 Digha field visit**

The Digha field visit took place on the 24th and 25th of April 2022, together with officials from the Department of Irrigation and Waterways. The figure below outlines the itinerary of the field trip with the locations visited indicated. This Annex 5 provides an overview of the most relevant observations during these two days.




The numbers in the figure above correspond to the numbering of the locations below.

(1a) Coast and sea dike southwest of New Digha

Observations at this location:

- Wide beach that is still accreting

- Accretion is decreasing (formerly 1 m per year in height, now reduced to 0.5 m)
- The area landward of the dike transitions from an area with buildings and Hotels (at New Digha) towards the west into an area with dunes and forest.
- The dike at this stretch of coastline seems to protect trees and elevated terrains. Details on the cost benefit ratio were asked, the proposed revetment structure seems to be costly, why not accepting some overflow, overtopping?
- The riprap revetment has been placed as a smooth surface, using smaller and larger stones. The smaller ones will be lifted during wave attack for sure. A true riprap revetment could reduce the impact of wave action, reducing crest level of overtopping discharges.
- The toe structure connects (beam and 3m sheetpile) to the slope. At this stretch there was no transition zone, riprap revetment or similar. Design lifespan of the structure was 10-20 years, which is short, considering the crucial position it has in the outer slope of the sea dike.

(1b) Coast and sea dike southwest of New Digha [eastern part]

Observations at this location:

- Beach observations were the same as at location 1a.
- The stone cladded dike at this stretch of coastline seems to protect trees and elevated terrains. Background of the cost benefit ratio not known. Why not accepting some overflow, overtopping?
- The connection between the cladded slope and the sandy beach is slightly eroding, opening up sight for the supporting sheet pile structure. A riprap revetment could reduce the impact of wave action, reducing scour along the toe of the structure.

- Design lifespan of the structure was 10-20 years, which is short, taking into account the crucial position it has in the outer slope of the sea dike.
- The horizontal alignment of the capping beam seems to vary considerably over its length, leaving unclear how the slope is settling. Possibly because of washing out of materials due seepage due to disconnections.
- The slope of the outer surface varies significantly of the length of the structure.
- The crest of the embankment is cladded as pavement. At the location of the absent inner slope, an environmental zone is situated. Performance under overtopping?

(2) Former mouth of Subarnarekha River

Observations at this location:

- This was supposedly the former mouth of the Subarnarekha River (a few centuries ago). The mouth has shifted westward and sediment supply from the hinterland to the coast has decreased. This has probably lead to sediment depletion of the coastline in front of Digha.

(3) Old Digha sea beach

Observations at this location:

- Solid coastal defence in place, riprap revetment over the entire length of the outer slope of the embankment.
- On the western side a concrete beam and sheet pile wall as toe structure, on the eastern side the revetment directly connected into the beach. Tetrapods to be paced on this side too, design philosophy for the existing structures not explained.

- Tetrapods can in principle dissipate wave energy and can capture sediment when sufficient sediment is supplied along the coast. In the current situation this is not yet the case.

(4) Viewpoint on Old Digha Sea Beach


Observations at this location:

- Between Old Digha Sea Beach Park and the viewpoint is a zone of coastal erosion, which probably relates to the construction of hard coastal defenses around the Old Digha Sea Beach Park, and the lack of sediment supply.
- Coastal dunes of heights up to 30m have eroded at the location of the viewpoint in the past 10 years.
- Eastward of the viewpoint a pocket beach has formed between the viewpoint and the spur (that both extend out into the sea).
- Outer slope well protected by concrete slabs with a 'roughened' profile. Revetment seems to be in good conditions, no erosion along the concrete beam type of toe structure.

(5) Spur at Digha Mohana

Observations at this location:

- The spur is effective at trapping sediment in front of the fishing village of Digha Mohana (left picture). Based on the sedimentation speed and sediment transport rate, which can contribute to a sediment budget.
- The spur is effective at keeping the waterway open for the fishers (right picture).
- The spur seems to be in good condition, the tailor-made tetrapods are keeping well.

- The main problem of the spur is that it prevents the longshore transport of sediment from here onwards to the east.
- Inflow of water into the river may have increased or may increase due to the spur.

(6) Shankarpur Sea Beach

Observations at this location:

- Coastal erosion occurred in the zone directly eastward of the spur over the past 10 years. Sediment supply to this area has reduced due to decreased inflow of sediment through the rivers (predominantly Subarnarekha River) and the spur at Digha Mohana.
- At this point there is a bend in the dike, with the dike being more seaward in the western part. The eastern part of the dike has completely been destroyed.
- Block revetment, supported by granular layer, being a large grading of stones without any geotextile layer.
- It was observed that 'roughened blocks were concreted on top of the revetments, rather than being an integral part of the blocks used for the revetment.
- The toe structure connects (beam and 3m sheetpile) to the slope. At this stretch there was no transition zone, riprap revetment or similar. Design lifespan of the structure was 10-20 years, which is short, considering the crucial position it has in the outer slope of the sea dike.

(7) Chandpur Sea Beach

Observations at this location:

- Coastal erosion occurred in the zone directly eastward of the spur. Sediment supply to this area has therefore been reduced due to decreased inflow of sediment through the rivers (predominantly Subarnarekha River) and the spur at Digha Mohana.
- Construction works on crest structure by vertically extending concrete walls, internally jointly connected. Not clear how interaction between extended core and slopes on sea and land side structurally interacts and in relation to overtopping.
- The sea side slope has a rip rap revetment, with no special structure at the toe of its slope. Potential impact of erosion, scour to be seen. Surveying and monitoring?

*Summary of main findings following from field visit*

- The Digha coast has been eroding for centuries and over large distances (Bandyopadhyay et al., 2009). The main reason for coastal degradation in Digha is therefore a structural shortage of sand.
- The original source of sand was the Subarnarekha River, providing a steady downdrift (northeastward) transport of sediment. This downdrift flux may have been disrupted at the source by the southward shift of the mouth of the Subarnarekha River and by the construction of upstream dams, barrages, and reservoirs that reduce sediment supply to the coast. The northward sediment flow is additionally disrupted by coastal constructions, such as the spur/jetty at Digha Mohana.
- The natural coast consisted of dunes (creating a natural sea defence as well as a buffer of sand to replenish coastal sections suffering from erosion) overgrown with vegetation (the salt-tolerant *Casuarina*) which traps wind-blown sand and strengthens the sand deposits.

- The lack of sand makes the dikes more vulnerable to breaching or damage during cyclones, because the sandy foreshore is of limited size and height. It is observed that embankments with a wide and high sandy foreshore remain intact.
- Hydraulic structures such as groynes and offshore breakwaters may be successful in locally trapping sediment and hence providing a local solution. However, the Digha coast system is an almost closed system of longshore sand transport. Therefore, trapping of sediment at one location will initiate erosion downdrift (northeast) of that location.
- A more sustainable solution is to nourish the Digha coastline. Sediment nourished at one location will locally lead to accretion of the beach and foreshore. This accreting beach / foreshore will migrate downdrift, supplying the coastlines northward of the suppletion. Nourishments need to be carried out repeatedly (where the interval depends on the volume of sediment supplied, e.g. yearly or once in a few years).
- Nourishments are not a replacement of embankments, but a way to protect the embankments. They thereby lead to lower maintenance and repair costs, also positively impacting on sea dike (re)construction cost. In combination with sufficiently high dunes, they may even make dikes obsolete. Also important, they strongly contribute to the esthetic value of the coastline, which is an important aspect for a tourist site.

*The following recommendations are made based on the field visit*

We believe that erosion rates are the result of shortage of sand. Such a sand shortage is problematic for the strengthening of sea dikes because sand is eroded from underneath these constructions, requiring very solid and deep dike toes. Any hard measure to trap sediment in one place will only lead to a larger sand shortage in another. This has probably happened as well by constructions of hotels close to the coast: the hotel constructions themselves (or measures to protect the hotels) lead to sediment shortage downdrift, which creates erosion problems there. The overall preferred strategy is to nourish sand (in addition to strengthening dikes). The Digha coast is well suited to nourishment because the sand remains relatively well trapped (in contrast to Sagar island). In order to evaluate the feasibility of nourishments, we recommend to:

- Make a sediment budget of annual sediment losses and sources, and estimate the long-shore sediment transport. The annual sediment loss is a first order estimate for the required annual nourishment volume. Those sediment budgets and transports can be estimated from the available data (measurements), and should also be cross-checked with estimated derived from simple coastline models (such as Unibest and ShorelineS).
- Make an inventory of sand availability offshore for dredging to be used for nourishment. This should include the particle size distribution, the thickness, and type of sand. Nourished sediments should preferably have approximately the same specifications as sand on the existing beaches (granulometry, color).
- Perform a cost-benefit analysis of the feasibility of nourishing. Costs include the required volume and dredging costs, and benefits should account for reduction in maintenance but also aspects such as Digha’s economy (wide beaches attract tourists)

*Construction of a deep sea Port*

There are plans to develop a deep deport at Tajpur. This means that many developments may take place at the coast, in front of the coast, as well as construction of inland infrastructure. The channel that will be dredged for the deep-sea port will act as a sink for sediment, and therefore influence the coastal dynamics. It is therefore recommended to understand the problem of coastal erosion and dike erosion in this area first and solve the problem. Any failure of coastal defences may have large consequences for newly planned infrastructure for the deep-sea port and should therefore be prevented.

## Annex 6 Design process (from International Levee Handbook)