Ministry of Water Resources

Bangladesh Water Development Board

Coastal Embankment Improvement Project, Phase-I (CEIP-I)

Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)

Component 5b: Coherence and Overall Picture of the Ganges-Brahmaputra Delta

June 2022

Joint Venture of DHI The expert in WATER ENVIRONMENTS & Deltares Enabling Delta Life in association with IWM Water Environment & Climate

University of Colorado, Boulder, USA
Columbia University, USA

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Office: Flat #3/B, House #4, Road #23/A, Banani, Dhaka 1213, BANGLADESH Phone +880 1307 693299

Memo No: CEIP/LTMRA/0622/177 19 June 2022

Project Management Unit
Coastal Embankment Improvement Project, Phase-I (CEIP-I)
Pani Bhaban, Level-10
72, Green Road, Dhaka-1205

Attn: Mr. Syed Hasan Imam, Project Director

Dear Mr Imam,

Subject: Submission of the report on Coherence and Overall picture of the Ganges-Brahmaputra Delta (D-5B)

It is our pleasure to submit herewith five copies of the Report titled ***"Component 5b:* Coherence and Overall picture of the Ganges-Brahmaputra Delta*"***.

This report provides an overall picture of the dynamics of the Ganges-Brahmaputra Delta, including the coherence between the various activities in components 3 (data collection) and 4 (modelling), and implications for the 5 focal coastal polders (15, 29, 40/1 & 40/2, 59/2 and 64/1a & 64/1b).

Thanking you,

Yours sincerely,

Dr Ranjit Galappatti
Team Leader

Copies: Engineer Fazlur Rashid, Director General, BWDB
Dr. Zia Uddin Baig, ADG (Planning), BWDB
Dr Kim Wium Olesen, Project Manager, DHI
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Mr Zahirul Haque Khan, Deputy Team Leader
Mr AKM Bodruddoza, Procurement Specialist
Swarna Kazi, Sr. Disaster Risk Management Specialist, World Bank

Contents

FIGURES

ACRONYMS AND ABBREVIATIONS

ADCP- Acoustic Doppler Current Profiler

BDP2100- Bangladesh Delta Plan 2100

BIWTA- Bangladesh Inland Water Transport Authority

BMD- Bangladesh Meteorological Department

BoB- Bay of Bengal

BWDB- Bangladesh Water Development Board

CBA- Coast Benefit Analysis

CCP- Chittagong Coastal Plain

CDMP-Comprehensive Disaster Management Program

CDSP- Char Development Settlement Project

CEA- Cost Effectiveness Analysis

CEGIS- Centre for Environmental and Geographic Information Services

CEIP- Coastal Embankment Improvement Project

CEP- Coastal Embankment Project

CERP-Coastal Embankment Rehabilitation Project

CPA- Chittagong Port Authority

CPP-Cyclone Protection Project

CSPS-Cyclone Shelter Preparatory Study

DDM- Department of Disaster Management

DEM- Digital Elevation Model

DOE- Department of Environment

EDP- Estuary Development Program

FAP- Flood Action Plan

FM- Flexible Mesh

GBM- Ganges Brahmaputra Meghna

GCM- General Circulation Model

GIS- Geographical Information System

GTPE- Ganges Tidal Plain East

GTPW- Ganges Tidal Plain West

HD- Hydrodynamic

InSAR- Interferometric Synthetic Aperture Radar

IPCC- Intergovernmental Panel for Climate Change

IPSWAM- Integrated Planning for Sustainable Water Management

IWM- Institute of Water Modelling

LCC- Life Cycle Costs

LGED- Local Government Engineering Department

LGI- local Government Institute

LRP- Land Reclamation Project

MCA- Multi Criteria Analysis

MES- Meghna Estuary Study

MoWR- Ministry of Water Resources

MPA- Mongla Port Authority

NAM - Nedbor Afstromnings Model

PPMM- Participatory Polder Management Model

PSD- Particle Size Distribution

RCP- Representative Concentration Pathways

RTK- Real-Time Kinematic

SET-MH- Surface Elevation Tables – Marker Horizons

SLR- Sea Level Rise

SOB- Survey of Bangladesh

SSC- Suspended Sediment Concentration

SWRM- South West Region Model

TBM- Temporary Bench Mark

TRM- Tidal river Management

ToR- Terms of Reference

WARPO- Water Resources Planning Organization

WL - Water Level

1 Introduction

1.1 Scope of work

The project ‘Long term monitoring, research and analysis of Bangladesh Zone’ (hereafter referred to as LTMRA) focusses on ’research, monitoring, and analyses of Bangladesh coastal zone towards long term sustainable polder development and management with attention to geo-morphological, environmental, economic and ecological aspects’. As part of this project a large amount of data has been collected and specific modelling studies have been carried out at various time and spatial scales on the impact of climate change and human interventions on salt intrusion, morphological changes, bank erosion, and polder drainage. These studies provide input for a polder management and investment plan as a final outcome of the project. One of the tasks of the project is to synthesize the various modelling studies into a coherent description of the present-day functioning of the delta, the impact of climate change on these dynamics, and implications for polder design (Component 5b).

The overall aim of Component 5b of the project ‘Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)’ is to provide an overall picture of the dynamics of the Ganges-Brahmaputra Delta, including the coherence between the various activities in components 3 (data collection) and 4 (modelling), and implications for the 5 focal polders within the project (Figure 1-1). The objectives of this work are defined in the Request for Proposals for Package No. CEIP-1/C3/S419 (November 2015):

- Obtain an overall picture of the delta dynamics in the future
- Obtain a picture of (the need for) possible large-scale interference in the coastal zone of the delta to reach optimal living conditions
- Quantify the mutual effects of physical processes (meteorology, tides, storm surges, sea level rise, morphology, salinity) and obtain an indication where more research is needed

The defined activities defined for component 5b are the following

1. Describe the interdependencies and mutual effects in detail, also based on the outcome of the studies in component 4 (modelling);
2. Quantify these for the future and indicate possible consequences for the boundary conditions for the polders (water levels, salinity, erosion and sedimentation patterns, subsidence, etc.);
3. Investigate the need or desirability of large-scale changes in the coastal zone (river diversions, damming river mouths, etc.) based on the results of activity 2, component 5A (polder design).

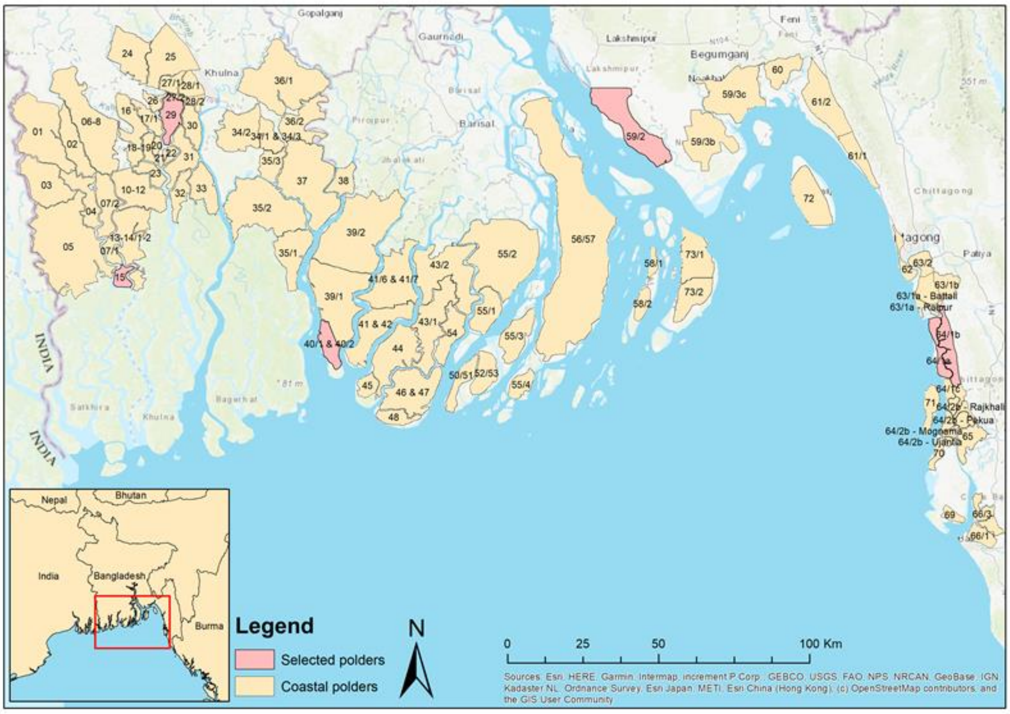

Figure 1-1 Map with coastal polders in the Ganges-Brahmaputra delta. With the 5 focal polders of the project highlighted in red (polders 15, 29, 40/1 & 40/2, 59/2 and 64/1a & 64/1b

This results in the current report describing

- Interdependencies and relations between the processes shaping the present-day delta on various time and spatial scales,
- The impact of human interventions (in the past and in the future),
- The impact of climate change,
- The consequences for the boundary conditions of the polders (in general, but especially focussing on the five selected polders – see Figure 1-1),
- Recommendations for future action plan/research (white spots, inexplicable phenomena),
- Potential large-scale interventions.

1.2 Approach and setup of the report

The general approach followed in this report is as follows. The dynamics of the delta are first evaluated at four spatial scales (the mega-scale, macro-scale, meso-scale, and micro-scale) based on available scientific literature and on results of the ‘Long term monitoring, research and analysis of Bangladesh Zone’ project (Chapter 2). At the mega-scale the functioning of the delta as a whole is described, notably the input of water and sediment towards the delta (and historic changes therein). The macro-scale dynamics covers the internal redistribution of water and sediment over the various distributaries, whereas individual distributaries themselves constitute the meso-scale dynamics. The micro-scale dynamics apply to the individual polders and small-scale river systems draining the polders. The analysis in Chapter 2 includes natural processes, but also the impact of historic human interventions.

The future development of the delta, described in Chapter 3, primarily draws on results from the LTMRA project. It includes a translation of global climate change predictions into a change in (mega-scale) water discharge and sediment loads. These changes are input for the macro-scale models, projecting the redistribution of water and sediment over the delta, which in turn feed into meso- and then micro-scale models. Several human interventions that are expected in the coming decades are identified and their impact evaluated with the aid of the developed numerical models. Also, the hydrological and morphological impact of a number of potential mitigating measures developed by the LTMRA project group throughout the course of the LTMRA project are evaluated with the developed models.

The impact of present-day and future changes (as described in Chapter 2 and 3) on polders is evaluated in Chapter 4. This chapter brings together how the various macro-and meso-scale changes impact the delta, and how potential negative impacts can be (partly) alleviated by mitigating measures.

Chapter 5 summarizes the key findings on the future development of the delta and identifies key knowledge gaps. The recommendations (Chapter 6) include suggestions for potential interventions, needs for monitoring, and future activities.

2 Present-day delta dynamics: a synthesis

The current state of the delta dynamics is described in this chapter by combining the information from the literature with insights from the field data and model results obtained in the present study. This description is done at four spatial scales in the following sections. These four scales are defined as follows:

- The **mega-scale**: the development of the entire delta,
- The **macro-scale**: distribution of water and sediment over the various distributaries through bifurcations,
- The **meso-scale**: distribution of water and sediment within the various primary distributaries (as indicated in Figure 2-2) and in-between distributaries through secondary channels (referred to as connecting channels),
- The **micro-scale**: distribution of water and sediment within polders and the blind peripheral rivers connecting the polders to the primary distributaries.

2.1 Mega-scale development

At the largest scale, the mega-scale level, the delta as a whole is considered, at which its morphological development depends on the sediment budget and relative sea level rise. The sediment budget of the delta can be analysed by considering the sediment input from the rivers, sediment output (leaving the delta) and sedimentation within the delta. Estimates of the total sediment reaching the GBM delta vary between 0.6–2.4 billion tons per year (Rahman et al., 2018), with the most reported value of around 1.1 billion ton/yr. This wide range in estimates is due to different measurement techniques, and assessments being undertaken over different time frames and in different locations. The high-end estimate of 2.4 billion ton/yr is from an early study of Holeman (1968), and the low-end estimate comes from a recent study by Rahman et al. (2018) who did an extended literature review and analysed the sediment concentration data (1960–2008) collected by Bangladesh Water Development Board.

Based on the data in the period between 1960 and 2008, Rahman et al. (2018) detected a decreasing trend of the sediment load from the Ganges river of 4 MT/yr for the period 1980 onwards (Figure 2-1). Extrapolation of this trend yields a sediment load from the Ganges river to the GBM delta of 220 MT/yr in 2015. For the Brahmaputra a decreasing trend of 6 MT/yr is found from 1990 onwards. Extrapolation of this trend yields a sediment load from the Ganges river to the GBM delta of 250 MT/yr in 2015. The total fluvial sediment load to the GBM delta is thus estimated to be about 500 MT/yr, about 50% lower than generally assumed. The damping of the effect of the 1950 Assam earthquake (which elevated sediment transport rates for several decades) is considered as a possible cause of the decreasing trend in the fluvial sediment input to the delta (Sarker et al., 2009). There is thus still significant uncertainty about the present fluvial sediment input to the delta.

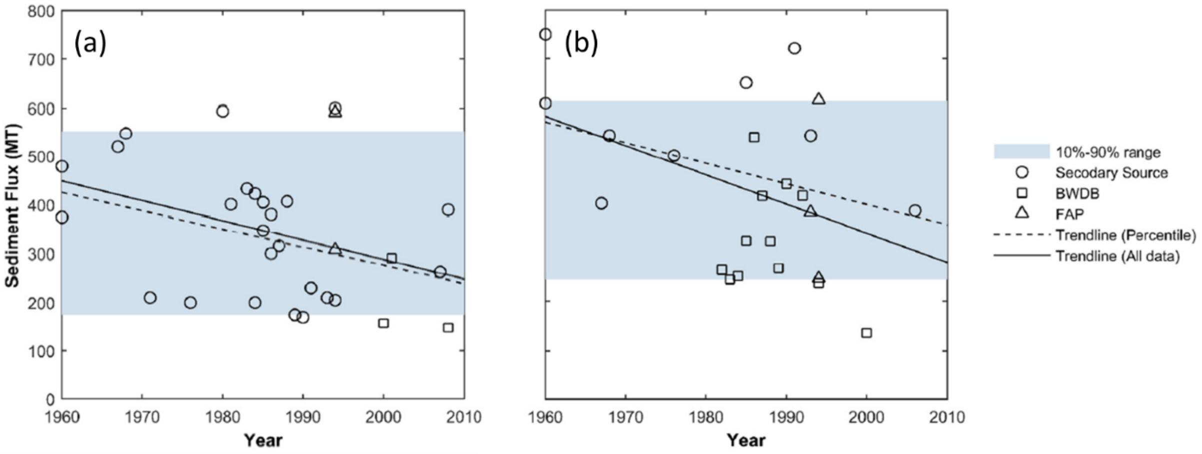

Figure 2-1 Sediment flux in the Ganges River at Hardinge bridge (a) and the Brahmaputra River at Bahadurabad using various sources of information (see Rahman et al. (2018) for details). From Rahman et al. (2018).

2.2 Macro-scale development

At the macro-scale the distribution of the fluvial sediment input within the delta (Figure 2-2) and the morphological developments of the large parts of the delta are considered. The present-day Ganges-Brahmaputra-Meghna system discharges most of its water and sediment through the easternmost outlet, the Meghna estuary. However, 18000 – 7000 years ago much more water (especially the Ganges discharge) was conveyed by the western outlets (the present-day Sundarbans channels, the Gorai and Hooghly estuary) (Goodbred and Kuehl, 2000). Major changes in the system also still took place in the past 250 years, as illustrated in Figure 2-3. In 1776 the Ganges river discharged directly into the Bay of Bengal, while the combined Brahmaputra-Meghna rivers had a separate outlet east of the Ganges. Only when the Brahmaputra changed its course in 1776 and flowed into the Ganges river, the present-day combined Meghna Estuary outlet developed.

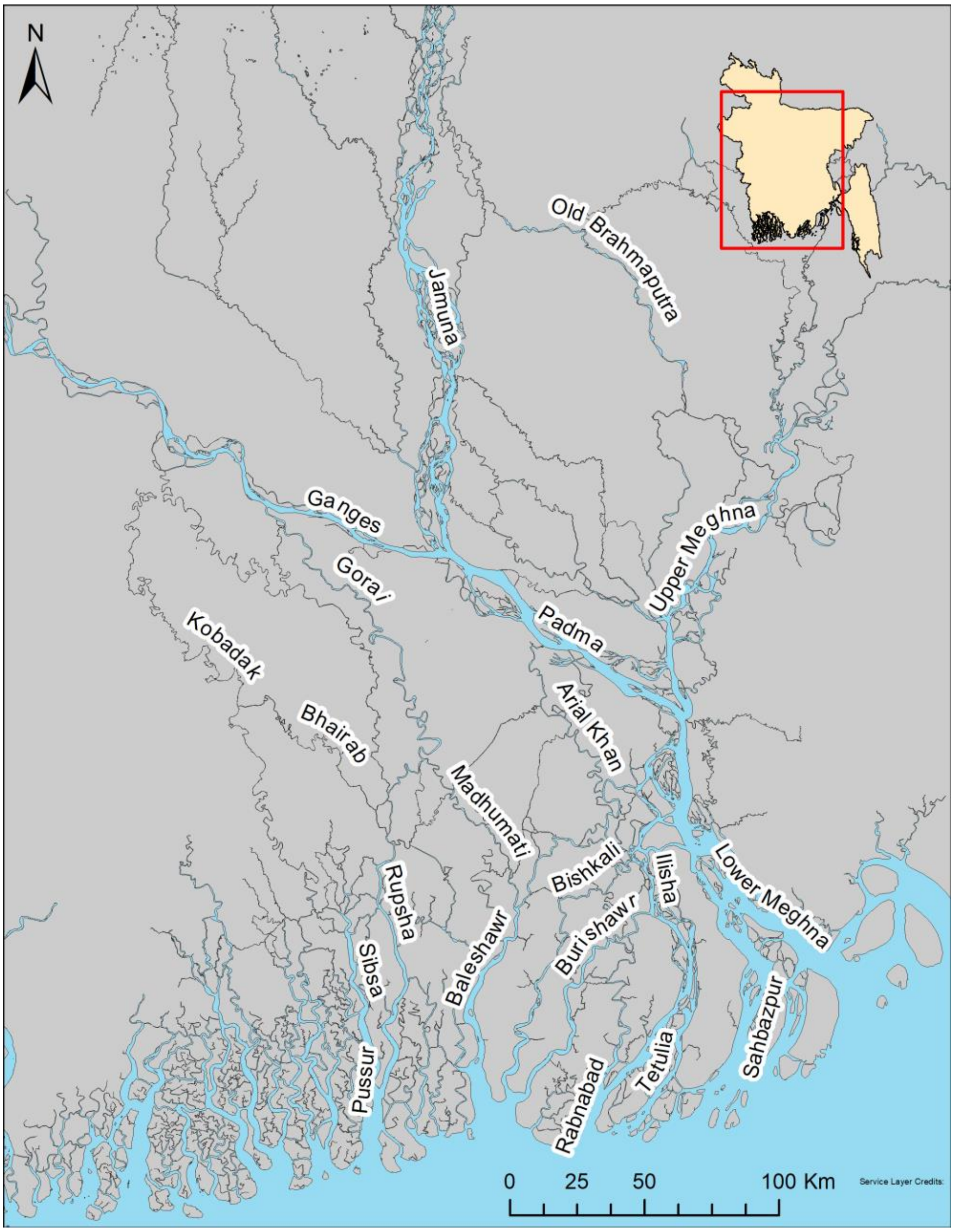

Figure 2-2 Map of the GBM delta with names of the various distributaries

The Ganges river has two distributaries in the delta (before joining the Brahmaputra to become the Padma river), the Hooghly river in India and the Gorai river in Bangladesh. The Padma river has one distributary (the Arial Khan river) before joining the Meghna river to become the Meghna estuary. The Gorai supplies the Bangladesh part of the Sundarbans with freshwater and sediment and the Arial Khan river the middle and embanked part of the delta. Both the Gorai river and the Arial Khan river transport ~5-10% of the total river discharge and sediment load -- 30 million ton/yr to the Gorai and 25 million ton/yr for the Arial Khan (Akter et al., 2015); most of the sediment load is diverted to the Meghna Estuary. For the dispersal of sediments, we follow the sediment budget by Paszkowski et al. (2021), being the most recent estimate and building on a wide range of historic literature (Figure 2-4).

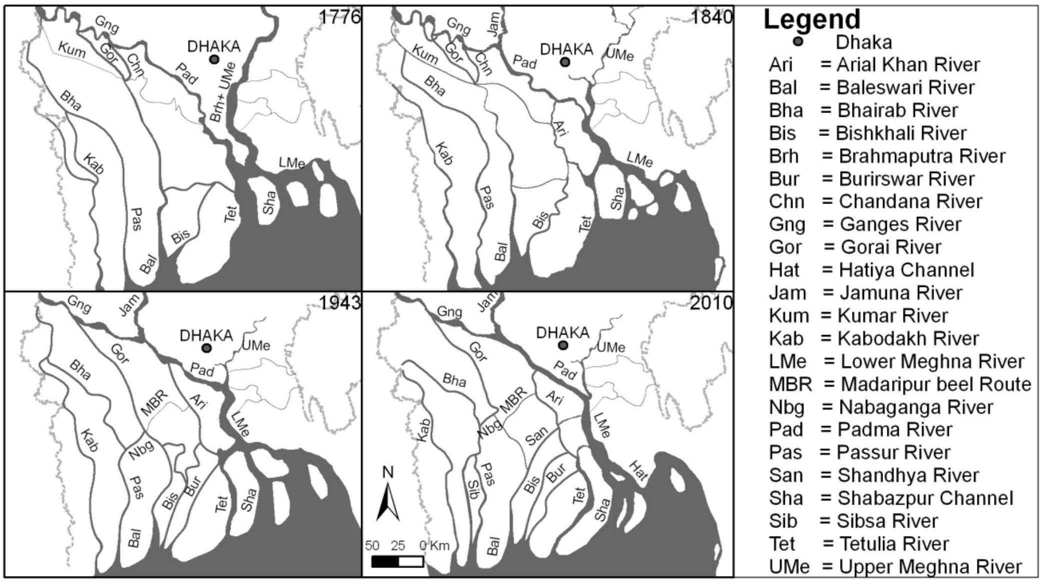

Figure 2-3 Development of the rivers in the Bengal delta over the past centuries (from Sarker et al., 2013).

According to this budget 70% of the sediment load is transported seaward by the Meghna estuary (with 10% diverted to the Hooghly river, 10% (in total) to the Gorai and Arial Khan rivers, and 10% depositing on the floodplains of the Brahmaputra river). Most of the sediment passing through the Meghna estuary is conveyed to the subaqueous delta (20%) and the offshore Bengal fan (20%). Another 20% deposits near the morphodynamically active mouth of the Meghna estuary, largely responsible for the annual land gain in the GBM delta of 17 km^2/yr for the last five decades (Sarker et al., 2013). The Meghna estuary is accommodation-space limited (i.e. the amount of sediment depositing in the estuary is limited by the available space, and not so much by the amount of sediment available) while many other parts of the delta are supply limited (net accretion is limited by the amount of available sediment) -see LTMRA-34 (Report nr. 34, Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone).

It is estimated that 10% of the total sediment is transported westward supplying sediments to the supply-limited estuary mouths west of the Meghna. This westward sediment transport was first observed by Barua et al. (1994), but the budget is based on average accretion rates in the lower delta plain / Sundarbans. Average accretion rates are 1.1 cm/yr (Kuehl et al., 2005) or 1 – 2 cm/yr (Hale et al., 2019). With a total area of 8561 km^2 (Nishat et al., 2019) each cm accretion requires about 85 million m^3 sediment. The bulk dry density of the deposited sediment varies between 670 – 1100 kg/m^3 according to the field measurement by Hale et al. (2019), implying 57 – 93 million ton/yr for every cm accretion (or 63 – 102 million ton/yr using Kuehl et al.'s 1.1 cm/yr). With a total sediment load of 500 – 1000 million ton per year of the Meghna estuary, it was argued that at least 10% of the total suspended load of the Ganges – Brahmaputra rivers is transported westward.

Figure 2-4 Sediment budget in the Ganges–Brahmaputra–Meghna delta system, from Paszkowski et al., 2021. Sources and sinks based on literature (see references in Paszkowski et al., 2021). Numbers represent percentage distributions of sediment entering (red) and leaving (orange) the delta, and dotted blue line represents the approximate location where the delta receives 100% of its sediment before depositing it downstream.

However, there are alternatives to this marine sediment supply mechanism. Sediment is not only supplied to the Sundarbans via the Gorai river, but also by the Arial Khan river and the Meghna estuary through the delta channel network, flowing into the Baleshwar (on the eastern boundary of the Sundarbans). The salinity of the Baleshwar river is much lower than in the Passur and Sibsa rivers (section 2.3.2). This means that Baleshwar river receives at least the same river discharge as the Passur and Sibsa rivers, suggesting that fluvial input is at least equal to the 30 million ton provided by the Gorai river to the Passur and Sibsa rivers (totalling 60 million ton/yr). In addition, bank erosion may also constitute a significant sediment source. Satellite images suggest that on average 16 million ton is released by bank erosion in the Passur-Sibsa estuary alone – see section 2.3.4. As a result, the marine sediment source may be smaller than the estimated 10% of the total sediment load. This may at least partly explain why numerical models did not reproduce the 10% westward transport (LTMRA-31).

The present-day delta is subsiding at rates of 3-9 mm/yr (results of component D-4B visualized in Figure 2-5 – see also Steckler et al., 2022). The variation of the subsidence rate is related to the sediment composition, especially the organic matter content. As an example, within the Passur - Sibsa system, the high subsidence rates in the Khulna region (~6 mm/yr) result from compaction of a high organic content in the palaeo-fluvial deltaic sediment whereas the lower subsidence rates around Mongla (4-5 mm/yr) reflect a higher mineralogical content (pers. comm. Steckler in Hale et al., 2019). Subsidence rates are highest in the Sundarbans (6-9 mm/yr). Observations by Hanebuth et al. (2013) reveal that the Sundarbans have been subsiding at high rates (5.2 mm/yr at the seaward edge) since at least the 17th century. Becker et al. (2020) report lower average subsidence rates in the Khulna – Mongla region (2.4 mm/), using on water level observations. In contrast to the map in Figure 2-5, their observations on water levels suggest that subsidence rates are highest in the delta in-between the Sundarbans and the Meghna estuary, averaging 7 mm/yr.

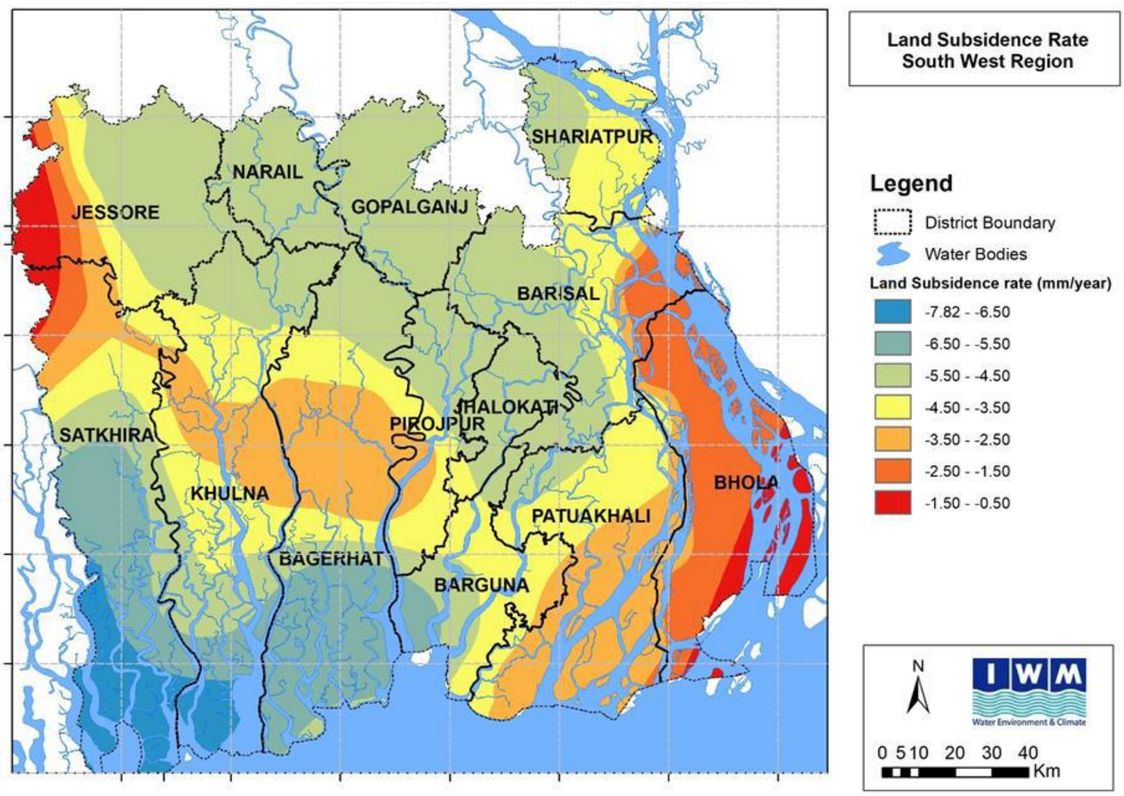

Figure 2-5 Subsidence rates [mm/yr] in the delta (results from component D-4B: Subsidence).

2.3 Meso-scale development

At the meso-scale the developments of individual estuaries (or distributaries) are considered. The various distributaries vary in two main aspects: (1) they are primarily tide-dominated (in the west) or river-dominated (in the east: the Meghna estuary and its primary distributaries), and (2) they are fully embanked (eastern section) or partially intersecting the Sundarbans mangrove forest (the tide-dominated eastern section). Key meso-scale issues are related to

- Water levels, especially high waters resulting from storm surges and tidal amplification,
- Salt intrusion,
- Riverbank erosion,
- The sediment budget (sinks, sources, and transport mechanisms) influencing navigability, infilling of secondary channels (see also section 2.4) and land formation (especially in the Meghna estuary).

2.3.1 Water levels

The key importance of water levels is related to flooding (high water levels) and drainage (period in a tidal cycle with water level below the water level in a polder). Water levels are a combination of the (relative) mean sea level, tidal variation, and storm surges.

Mean sea level

The relative mean sea levels are gradually increasing because of sea level rise (3 mm/yr; Pethick and Orford, 2013) and subsidence (3-9 mm/yr in the southwest delta; Figure 2-5).

Tidal range

The tidal range in the delta is around 2.5 meter at the mouth of the various distributaries, determined by the tides in the Bay of Bengal. In the eastern distributaries the tidal range quickly decrease due to bed friction and the mean river flow. However, in the western distributaries the tidal range increases in the landward direction (Figure 2-6) to values over 5 meters (Figure 2-7).

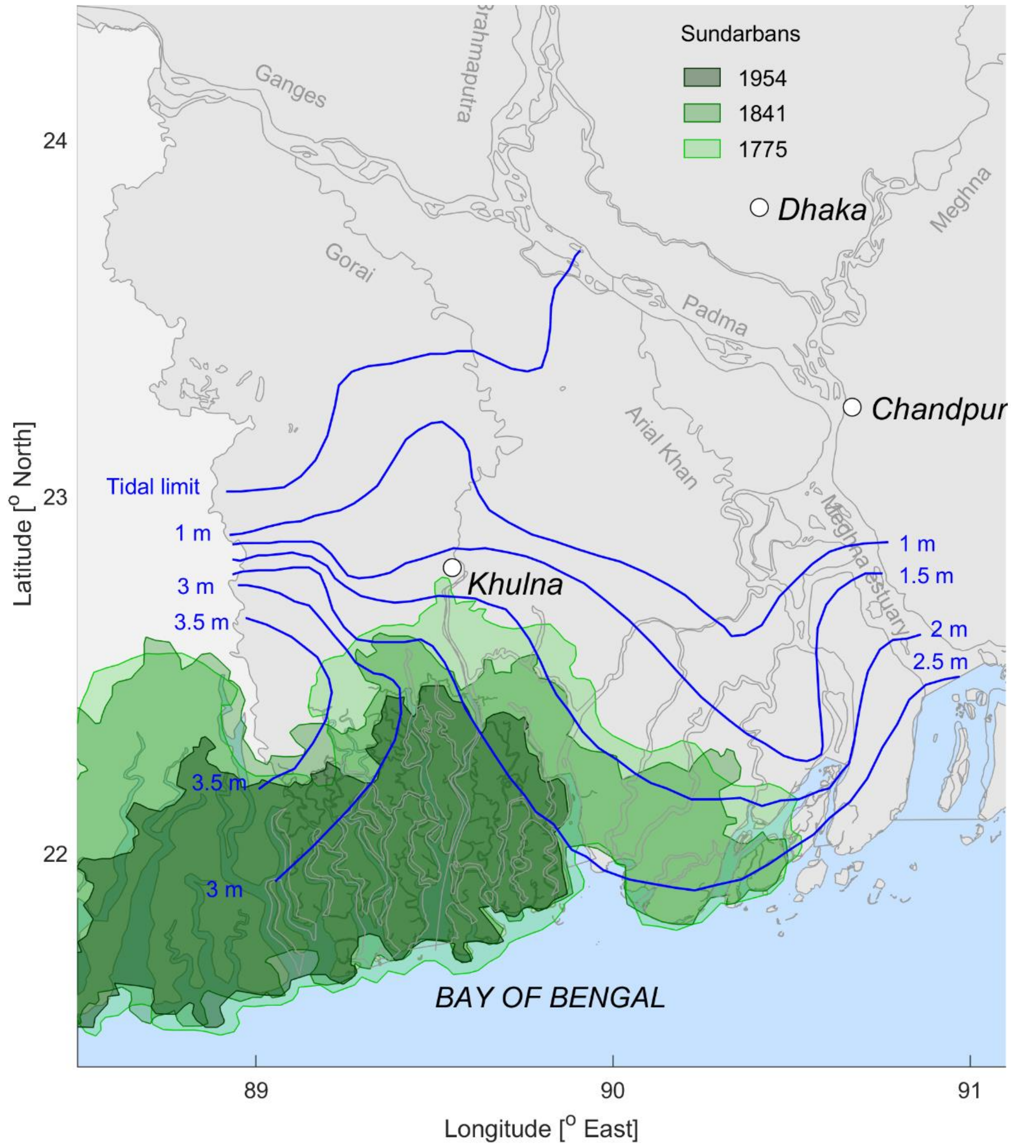

Figure 2-6 Approximate tidal range in the GBM delta (based on IWM data) with the main rivers, cities, and historic extent of the Sundarbans (from Nishat et al., 2019). The extent of the Sundarbans has decreased slightly since 1954 in India but has remained unchanged in Bangladesh. The tidal range is based on historic data which may not be representative for the western delta (see text).

The tidal range has been increasing since the construction of polders. Longest tidal records are available along the Passur and Sibsa river, where the tidal range increased from ~3 meter in 1940 to ~5 meter in 2020. In the same period the highwater levels increased with 1.5 meter. This increase is only partly resulting from an increase in the relative mean sea level (subsidence + eustatic sea level rise, up to 0.5 meter). The main cause of higher highwaters is the amplification of the tides (increase of the tidal range over time and/or space). Although historic data is available only for the Passur – Sibsa basin, it is well possible that the distributaries west of the Passur – Sibsa basin experienced a similar tidal amplification. Tidal changes in the eastern delta have been less pronounced (Figure 2-6).

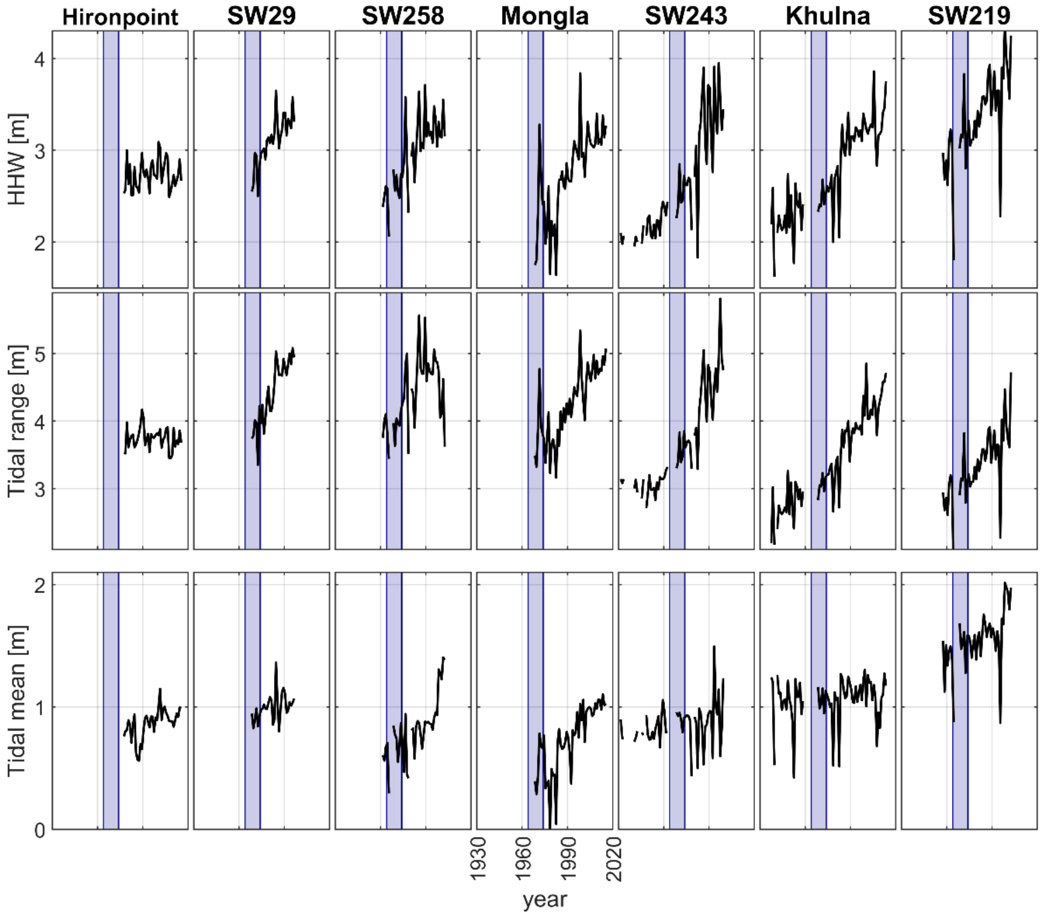

Figure 2-7 High water (HHW), tidal range, and mean water level in the 7 gauging stations of the Passur-Sibsa river, from 1930 to 2020. The blue bars denote the period of large-scale improvement of coastal embankments. From van Maren et al. (2022).

The reason why the tides continue to amplify, almost 60 years after the construction of polders, is related to two positive feedback mechanisms (Figure 2-8). The construction of polders led to gradual infilling of the blind peripheral channels. These channels drained intertidal and supratidal areas which were later reclaimed, and after reclamation no longer convey sufficient water to keep the channels open. These filled-in peripheral rivers no longer provide storage to dissipate the tides, leading to tidal amplification in the main channels (LTMRA-18, 2020 – see Figure 2-9a-c for a schematized picture). On top this, polder construction started earlier in the western GBM delta, as illustrated with chronological polder numbering (see Figure 1-1 for polder numbers). Polders were therefore developed in Sibsa estuary before those in the Passur estuary, leading to a faster tidal propagation in the Sibsa compared to the Passur (van Maren et al., 2022 – see Figure 2-9d and e). As a result, the tides from the Sibsa estuary propagated into the Passur estuary, thereby eroding the banks of the connecting rivers between the two estuaries. This allowed more water to tidal flow from the Sibsa to the Passur, leading to more erosion (and water discharge). The Passur estuary gradually carries less tidal flow, leading to channel shoaling in the Passur river around Mongla. This in turn reduces the propagation speed of the tidal wave in the Passur, further strengthening tidal flow through the connecting channels. This network reorganization has major implications for the polders, as elaborated in more detail in 2.4.

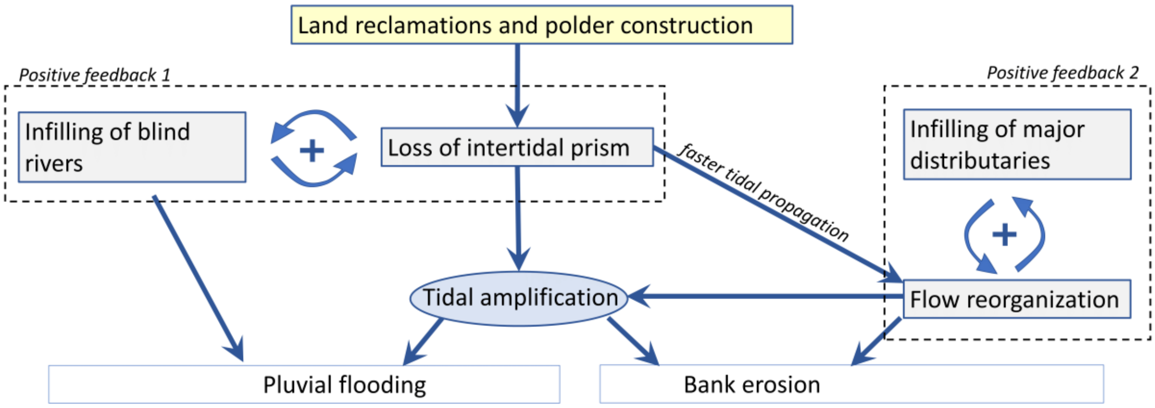

Figure 2-8 Conceptual diagram relating land reclamations and polder construction to tidal amplification, bank erosion, and pluvial flooding through two positive feedback mechanisms. See text for details. From van Maren et al. (2022).

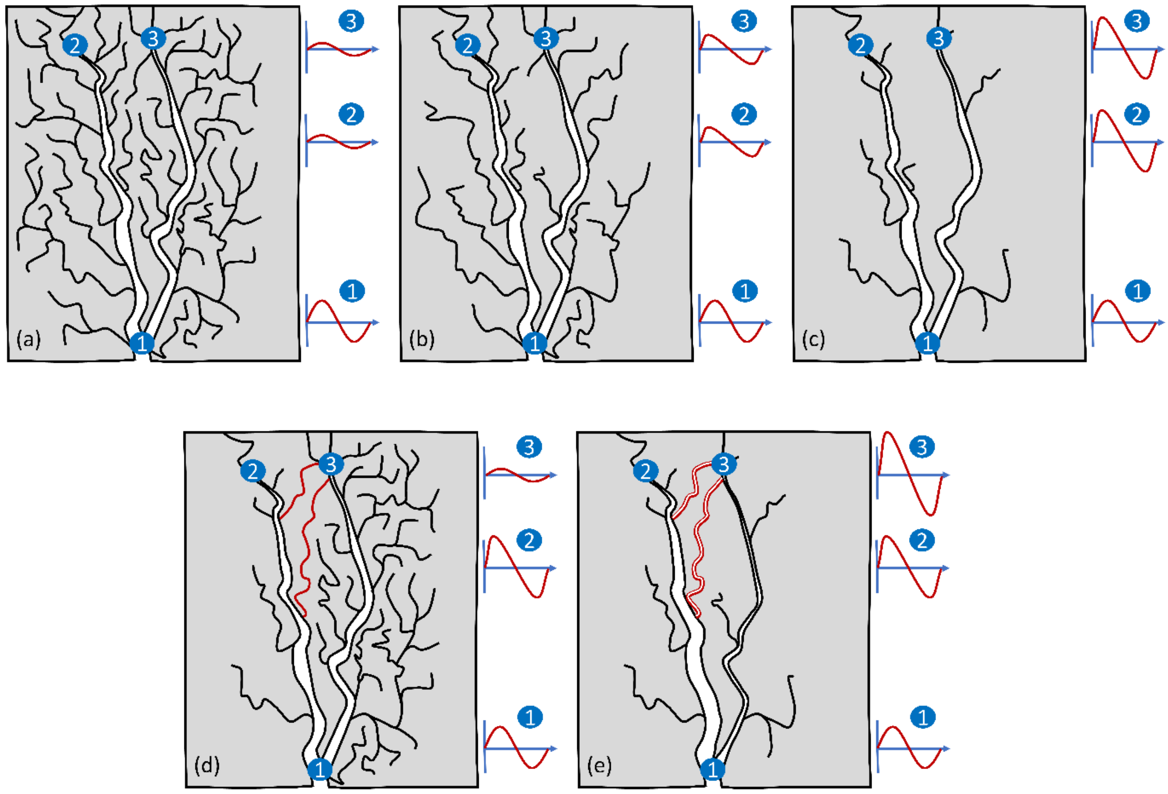

Figure 2-9 Positive feedback mechanisms leading to tidal deformation and channel network reorganization. Loss of the intertidal area leads to tidal amplification (b) relative to pristine conditions (a), strengthened by subsequent infilling of blind peripheral channels (c). On top of this, reclamation of the Sibsa basin before the Passur basin (d) leads to tidal deformation in the Sibsa and channel capture from the Passur basin. The connecting channels and the Sibsa expand while the Passur degenerates. From van Maren et al. (2022).

Storm surges

Even though the increase in tide-induced highwater levels threaten poorly protected low-lying areas, failure of embankments will only take place during cyclonic storms. Cyclones generated in the Indian ocean and Bay of Bengal result in storm surges up to 10 meter in the period 1960-2000 (Jakobsen et al., 2006). The devastating cyclone that occurred in 1876 may have led to a surge level as high as 14 meters (Jakobsen et al., 2006). However, these extreme peaks are confined to the north-east corner of the Bay of Bengal (east of the Meghna estuary) – the storm surge level in the larger part of the delta is closer to around 4 meters. A compilation of the most severe cyclones that occurred in the period 1960-2020 is included in LTMRA-49 (2021), showing that the majority of severe storms make landfall east of the Meghna estuary (Figure 2-10). The extreme water levels resulting from these events will be elaborated in more detail in Section 2.4.

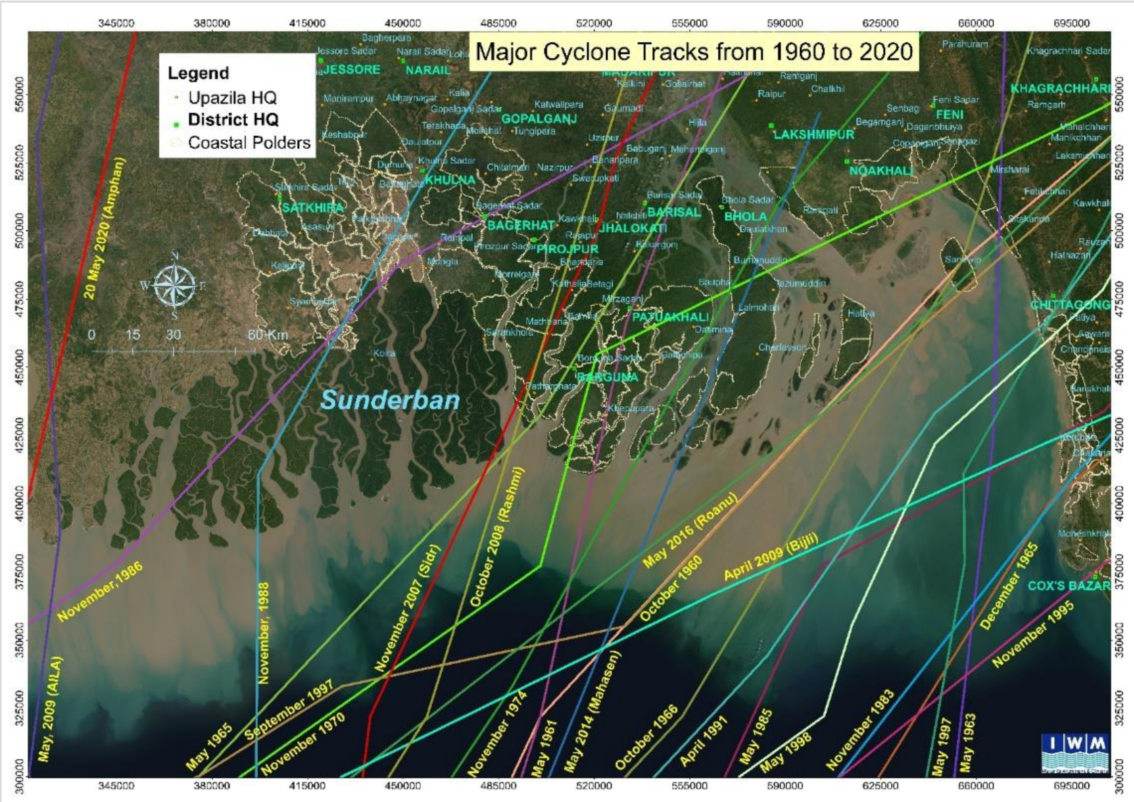

Figure 2-10 Historical severe cyclone track in the Bay of Bengal covering the Bangladesh Coast since 1960. From LTMRA-49 (2021).

2.3.2 Salt intrusion

The salinity in the delta varies over time and space. The eastern outlets are primarily fresh because of the high river discharge, whereas salinity increases towards the west (because of lower river discharge): see Figure 2-11. Especially in the dry season saltwater intrudes far into the western distributaries, negatively impacting agricultural land and drinking water availability. A salinity value of 2 ppt is the threshold value for irrigation and agricultural purposes (LTMRA-49). East of the Baleshwar river the majority of the polder region receives sufficient fresh water, whereas as the seaward located polders west of the Baleshwar river experience salinity values exceeding this critical limit of 2 ppt (Figure 2-11). In such saline areas shrimp farming is an important source of income. In the past decades, there has been a gradual transition in the high-salinity areas from agriculture to shrimp farming, which is related to a change in river discharge in the western delta.

The salinity in the delta has been especially influenced by changes in water flow through the Gorai river which in turn has been strongly influenced by the Farakka Barrage. This barrage was constructed along the Ganges river between 1962 and 1970 in India, just upstream of Bangladesh.

The result was a reduction of the river discharge in the dry season of the entire Ganges river and its distributaries downstream of Farrakka barrage. This resulted in lower dry season water levels in the Ganges river which in turn led to a reduction of discharge from the Ganges to distributaries flowing southward into the delta. The most important distributary is the Gorai river.

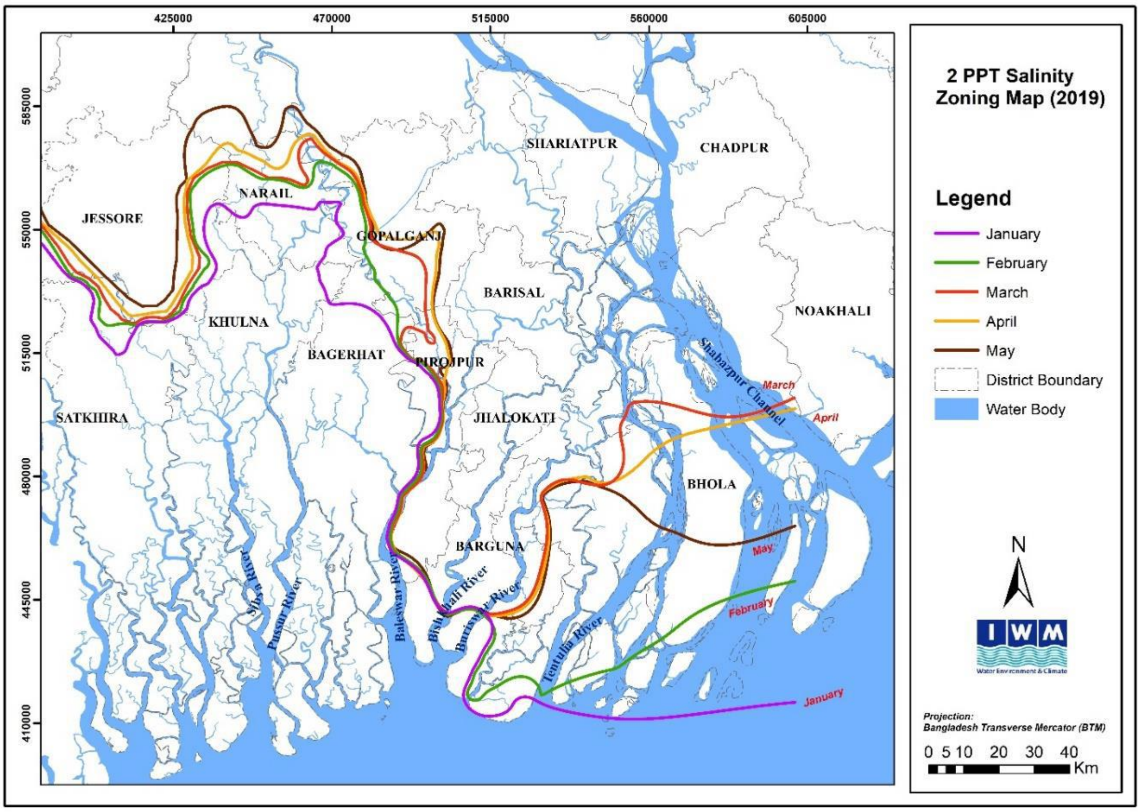

Figure 2-11 Observed salt intrusion limit of 2 ppt per month (January through May) in the dry season, based on continuous observations in 2019 (LTMRA-63).

The dry season discharge of the Gorai river is about 50% lower at present compared to the 1980's situation due to construction of the Farakka Barrage (Anwar et al., 2020) and the salinity in the delta increased accordingly. Before the construction of Farakka dam, the average monthly salinity at Khulna never exceeded 2 ppt whereas it exceeds 10 ppt in April and May since the Farakka Barrage became operational (Mirza, 1998). Dredging of the offtake from the Ganges from the Gorai river in 2012-2013 led to an increase in river discharge, resulting in a significant reduction of the salinity in the Gorai river (LTMRA-63).

But although this salinity is partly the result of the reduction of river discharge, it is also partly the result of tidal amplification. The tidal range near Khulna, for instance, increased from 3 m before 1960 (hence before construction of the Farakka barrage) to 4.5 m at present (Figure 2-7). And higher tidal amplitudes strengthen salt intrusion (especially in sediment-rich shallow river systems). Additionally, the river discharge diverted from the Gorai river through the Passur (via the Nobaganga river) has been increasing at the expense of the Madhumatu river (discharging into the Baleshwar river). Historic maps suggest that around 1900 the majority of the Gorai flow was diverted to the Madhumatu river. In 1960 the size of the Madhumatu and Nobaganga river was comparable, and discharge measurements executed at that time by NEDECO (1967) suggest that the discharge was evenly distributed among both branches. At present 85% of the Gorai river discharges into the Passur river (Azis and Paul, 2015). This means that the present-day discharge into the Passur river is probably comparable to the situation before poldering, but smaller than it was in the 1980's. The fresh water discharged into the Baleshwhar dramatically decreased. However, the salinity in the

Baleshwar river is much lower than in the Passur river (Figure 2-11) because it is connected to the Meghna estuary and the Arial Khan river as well.

Distributaries (in Bangladesh) west of the Gorai do no longer receive fresh water from the Ganges. The Kobadak river, the main system flowing into the Sibsa river, used to receive fresh water from the Mathabhanga river until the early 1970s. The reduction of freshwater flow through the Mathabhanga was therefore probably influenced by the construction of Farakka barrage as well. However, also before the 1970's the Mathabhanga river was already degenerating, carrying only a very small discharge component. As a consequence, the rivers in the southwestern delta have gradually become more saline by various river closures, but the salinity sharply increased because of the construction of the Farakka barrage.

2.3.3 Riverbank erosion

Bank erosion is a natural, widely occurring phenomenon in alluvial deltas due to lateral channel migration. We will evaluate riverbank erosion on 3 levels because of different underlying erosion mechanisms: (1) for the Meghna estuary, (2) for the other main distributaries, and (3) for the peripheral / connecting rivers. At present there is no or only very limited bank erosion along the blind peripheral rivers. Bank erosion near polders will be discussed in the section on bank erosion on a micro-scale (section 2.4.3).

The Meghna estuary

Both the east bank and the west bank of the Meghna estuary erode (see Figure 2-12 and Figure 2-13). At the same time, a middle bar develops in the central estuary which becomes larger (Figure 2-12 and Figure 2-13) and higher (less frequently inundated; see Figure 2-12). Both are interrelated: most likely the middle bar pushes the river and tidal flow sideways, resulting in bank erosion.

Morphologically the estuary is extremely dynamic, with erosion rates up to 10 km in a 30-year period (over 300 m/yr; see Figure 2-14). Erosion rates are up to 200 m/yr near polder 59/2 and 56/57. An important observation is that the erosion rates are mostly constant (i.e. not accelerating or slowing down) until a sudden large-scale realignment takes place. An example is the gradual westward shift of the west bank in the top North of Figure 2-14 from 1988 to 2010 resulting from channel migration. Throughout the 1990's this westward migrating channel is the main channel in the Meghna but as it migrates further west it decreases in size. This western branch becomes gradually less important throughout the 2000's and around 2012 it degenerates to the small river it is today (Figure 2-13).

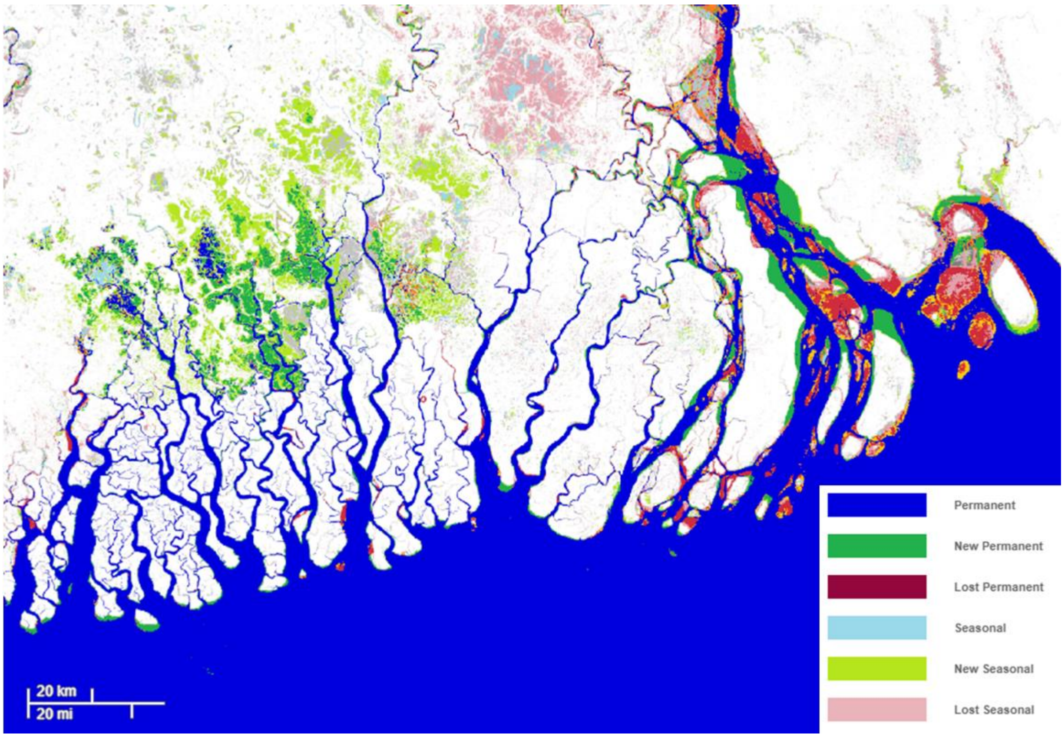

Figure 2-12 Flooding and drying map over the period 1984 – 2020, retrieved from http://global-surface-water.appspot.com/map. 'New permanent' refers to areas that were dry before 1984 but became permanent water bodies (such permanently flooded polders in the tide-dominated delta in the western delta and bank erosion in the Meghna estuary). 'Lost permanent' areas were water before 1984 but are now land (accretion, such as the mouth bar in the Meghna estuary). Seasonally flooded areas alternate between dry and wet conditions over the year (e.g. waterlogging during the wet season resulting from pluvial flooding).

Figure 2-13 Satellite image (from https://earthengine.google.com) of the Meghna estuary in 1984 and 2020. Detailed coastline changes (depicted with the white inset) in Figure 2-14.

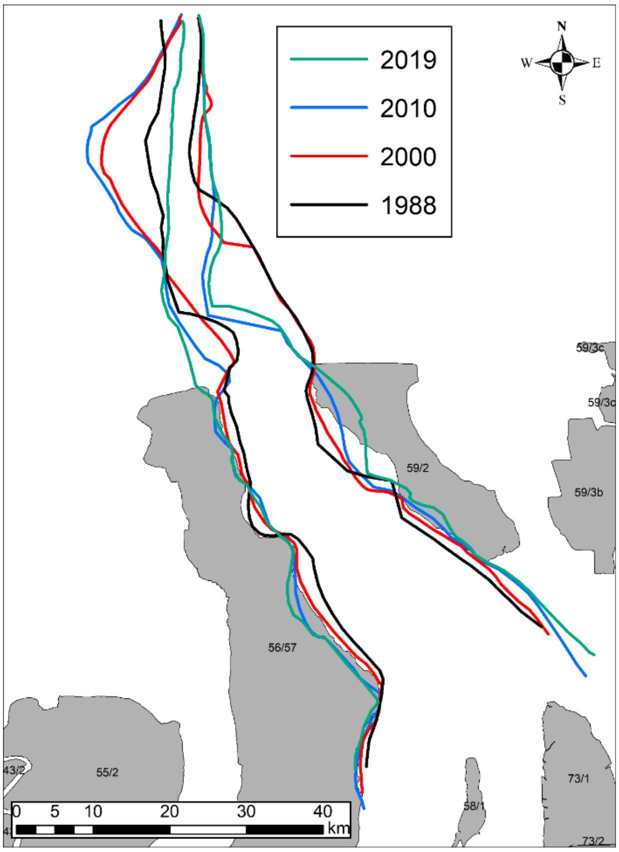

Figure 2-14 Digitized riverbanks in the middle Meghna estuary (see Figure 2-13 for location)

Other main distributaries

The various distributaries west of the Meghna migrate laterally at much lower rates, which is analysed in detail in the bank erosion reports (LTMRA-29, 30, and 37). It has been found that the locations of bank erosion remain the same on a decadal timescale and that the erosion rates are more or less constant in time: as a result, the bank erosion rates are fairly predictable. The maximum erosion rates are remarkably similar for the various subsystems (15 – 20 m/yr, see Figure 2-15). We can differentiate two mechanisms responsible for erosion:

- Lateral migration (where the outer bend erodes and the inner bend accretes, resulting in limited change in channel width over longer timescales). This is the dominant bank erosion type and results in the sinusoidal pattern of bank line change in Figure 2-15.

- Channel expansion (where the channel width increases). The majority of the channels experience net erosion (superimposed on the lateral migration). Net channel erosion occurs in the Sibsa seaward of KM 480; in the Passur seaward of km 480 and landward of km 495 and in the Baleshwar landward of km 455.

Only the Passur river between the port of Mongla and its connection with the Sibsa (km 480 – 495 in Figure 2-15b) experiences a structural channel width decrease. This channel shrinking is the result of channel network reconfiguration because progressively more tidal flow in the upper Passur is provided by the Sibsa at the expense of the lower Passur river – see LTMRA-18 or van Maren et al. (2022).

The net channel width expansion is commonly a response to an external change to the system (local human interventions or changes in upstream water and/or sediment supply). For the Passur and the Sibsa the main external change is the polder construction which led to change in tidal flow and channel network reconfiguration (van Maren et al., 2022). Superimposed on the average channel expansion is lateral migration, which can be identified as bank erosion on one bank being compensated by accretion on the other side – over longer periods of time the channel width remains constant.

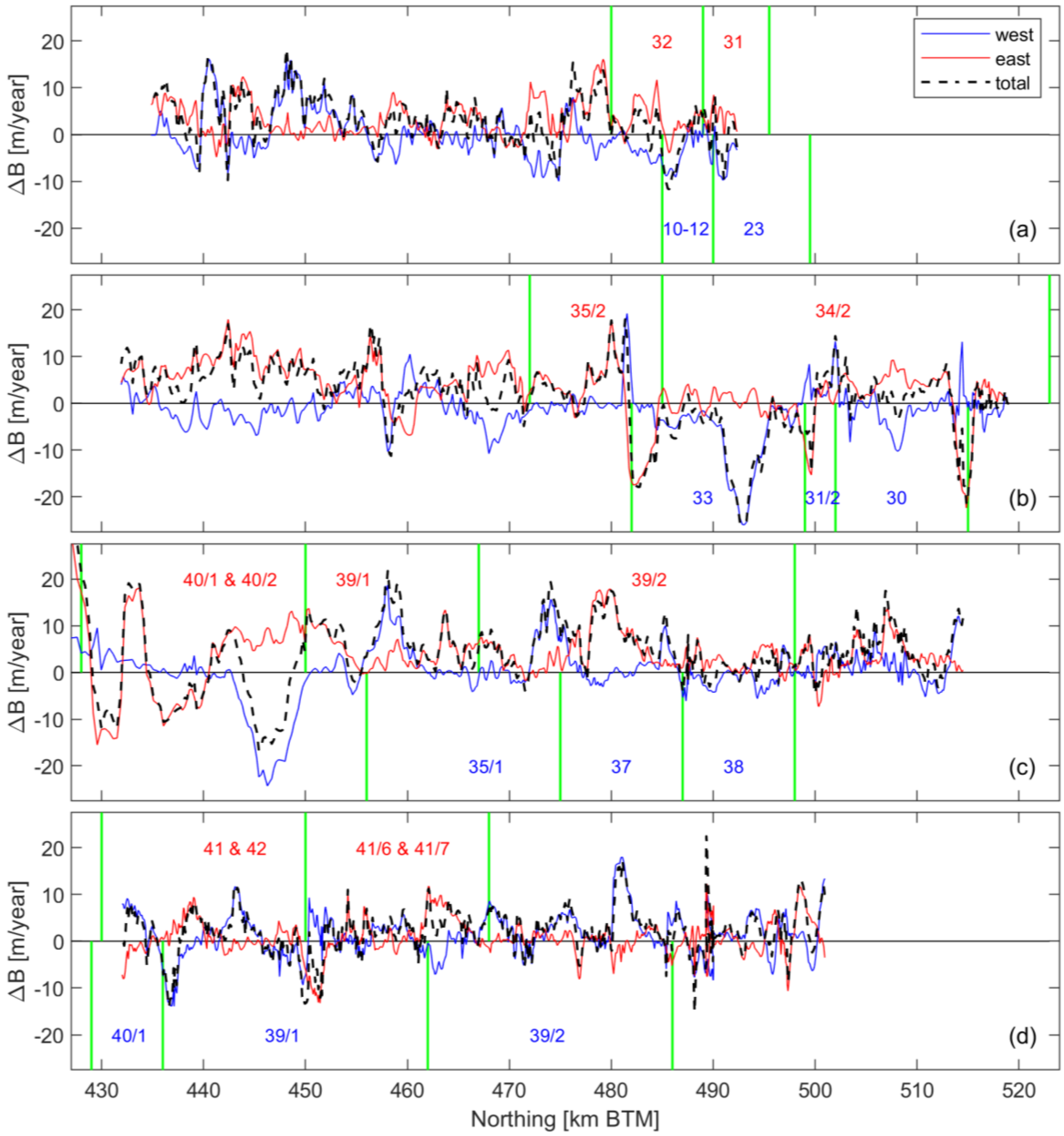

Figure 2-15 Bank migration ΔB (from LTMRA-29, 30, and 37) per riverbank and over the cross-section (in meter, erosion is positive for both east and west river banks) for the Sibsa river (a), the Passur river (b), the Baleswar river (c) and the Bishkhali river (d). The distance along the rivers is in Northing (positive values in the landward direction) for easy comparison with the polders. The polders along the west riverbanks are in blue; polders along the east riverbank in red. Polder boundaries are in green.

Peripheral rivers

Peripheral rivers are secondary rivers connecting the main distributaries with polders (blind peripheral rivers) or interconnecting the main distributaries (connecting peripheral rivers). The blind peripheral rivers fill in because of the low flow velocities in these rivers after polder construction, where bank erosion is not an issue. However, some connecting peripheral rivers experience large erosion rates. Especially the rivers connecting the Passur river with the Sibsa river are constantly widening. Before polder construction these rivers were quite marginal (appearing as very small rivers on pre-polder maps, or not existent at all). Construction of polders set in motion a process in which progressively more tidal flow originating from the Sibsa captures tidal prism from the Passur river, resulting in progressively more water flow through the connecting channels (Figure 2-8). The resulting widening of the channels has a fairly constant rate (i.e. not accelerating or slowing down – see Figure 2-16) and takes place throughout the whole depth of the channel (Figure 2-17).

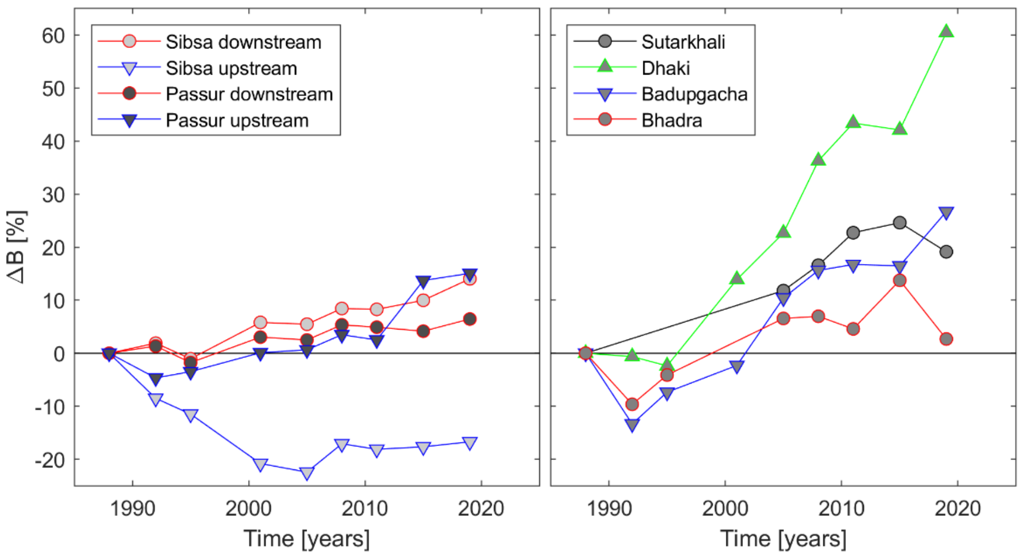

Figure 2-16 Change in average channel width ΔB (with an increase defined positive) relative to the channel width in 1988 in the distributary channels (a; upstream and downstream of the area with connecting rivers) and in the four connecting rivers themselves (b). ΔB is defined as the along-channel average of the longitudinal change in width (per year). From van Maren et al. (2022).

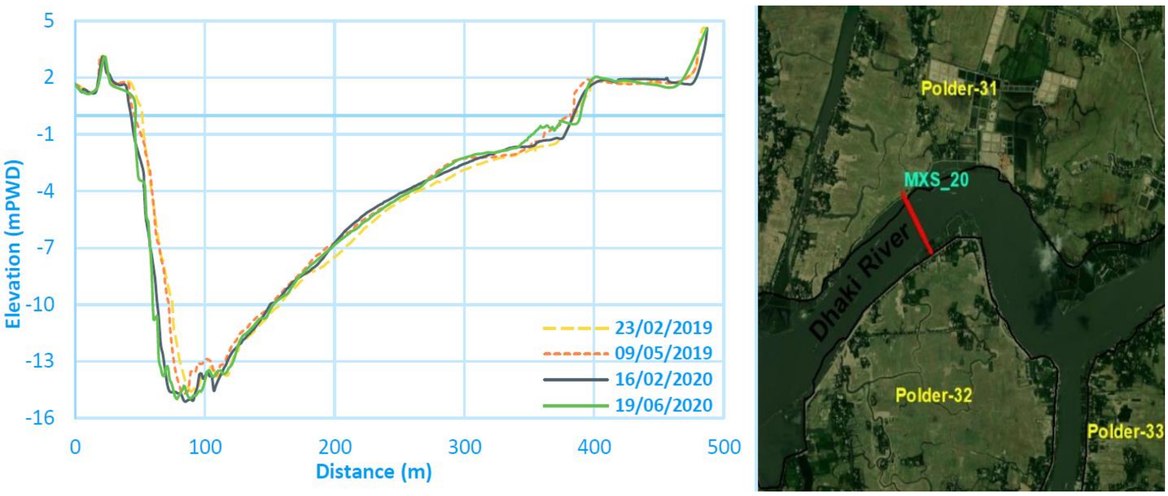

Figure 2-17 Monitoring section-20 of the Dhaki river, a connecting river between the Passur and Sibsa river (report Monitoring Results on Sedimentation rate in rivers and Floodplain)

2.3.4 Sediment budget

The sediment budget in the various distributaries is governed by sinks, sources, and transport mechanisms. Three sediment sources exist: the rivers, the Bay of Bengal, and riverbank erosion. The main sediment source for the delta is river flow. The present sediment input from the rivers is uncertain, with estimations varying from approximately 500 million ton/yr to 1200 million ton/yr (see Section 2.1). Most of the sediment is provided to the Meghna estuary, which is transported seaward by river flow. The distributaries receive progressively less sediment in the westward direction. For these western distributaries, the Bay of Bengal provides an additional sediment source. This sediment stems from outflow of the Meghna estuary and is estimated at about 10% of the total (or 50 million ton/yr), which is transported westwards by prevailing currents (Barua et al., 1994). This corresponds to approximately 10 million ton/yr per distributary (Paszkowski et al., 2021) which corresponds to the ~10 million ton/yr sediment import into the Passur - Sibsa river computed with a three-dimensional sediment transport model (LTMRA-18, 2020). This sediment import provides a major uncertainty though, because in situ observations of the sediment concentration in the northern Bay of Bengal are scarce. Observations have only been reported by Barua et al. (1994) and Rice (2007), suggesting the sediment concentration is probably several 0.1 g/l. Additionally, the large-scale sediment budget does not account for bank erosion. Only in the Passur - Sibsa estuary the annual release of sediment due to channel widening is 16 million ton/yr (Figure 2-18).

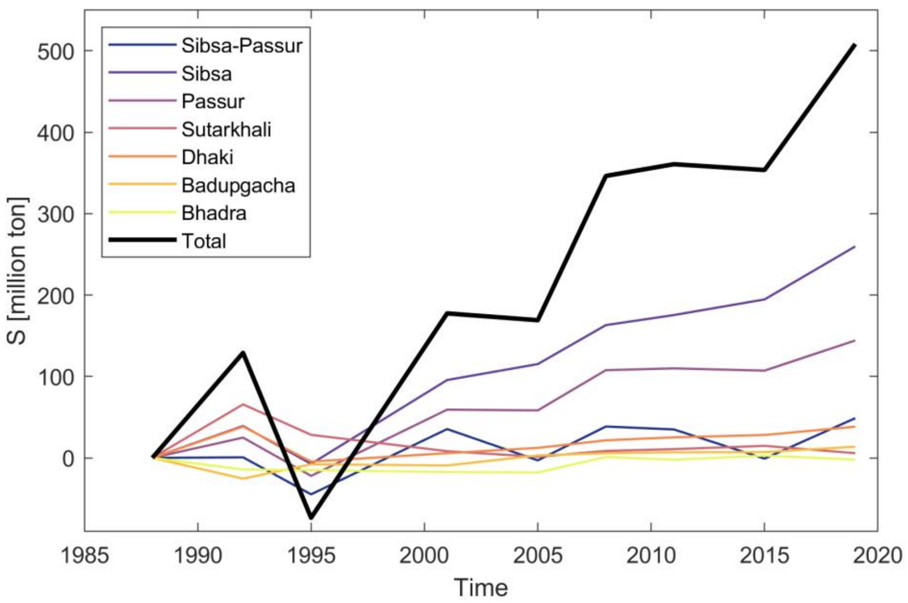

Figure 2-18 Cumulative eroded sediment mass resulting from channel widening (sediment supply by bank erosion compensated for sediment deposition on the on the other bank), computed from satellite images (from 1988 to 2019) and assuming a channel depth of 15 meter in the combined Sibsa-Passur channel decreasing to 5 meter in the upper Passur and Sibsa rivers and of 10 meter for the other rivers.

The main sediment sinks are infilling peripheral channels, the Sundarbans, and channel aggradation. Largest channel aggradation takes place in the Meghna estuary. The existing mid-channel and mouth bars are largely accreting and expanding in size (Figure 2-12). These deposits sequester around 20% of the annual sediment load discharged by the Ganges – Brahmaputra rivers (Paszkowski et al., 2021) – roughly 100 - 200 million ton/yr. Continues aggradation also prevails in the Passur river, up to 0.3 m/yr resulting from channel network reorganization (LTMRA-18, 2020), resulting in a total infill of approximately 10 million ton/yr (van Maren et al., 2022). The Sundarbans sequester 63-102 million ton/yr (see section 2.2), providing the second-largest sediment sink. The contribution of infilling of blind peripheral rivers to the total sediment budget is more difficult to assess. Over 1000 km of peripheral rivers area filled up with sediments in the embanked part of southwest delta since the construction of the polders (approximately 20 km/yr), and at present 16 km of channels still close every year (Wilson, 2017). This probably amounts to several million ton/yr (a more detailed budget requires regular bathymetric surveys which are unavailable).

Sediment transport is directed from the sediment source to the sink by tidal and non-tidal currents. Most of the sediments transported in suspension in the southwest delta is very fine, and therefore the transport rate is not equal to the transport capacity. This means that the suspended load is not merely determined by the local hydrodynamic (flow velocity and water depth) and sedimentological conditions. Providing there is a mechanism that regularly suspends the sediments (tidal currents) the residual transport is primarily driven by sources and sinks (transporting sediment from high energy locations to low-energy conditions). As such, sediment is transported from the eroding riverbanks, upstream rivers, and Bay of Bengal to the Sundarbans and the blind peripheral rivers. Landward transport is further promoted by a pronounced flood-dominant tidal asymmetry and salinity-driven estuarine circulation (LTMRA-18, 2020).

Sediment transport in the Meghna estuary is closer to capacity conditions as the transported sediment is coarser (large amount of fine sand and silt carried in suspension, median grain size of bed sediment is 0.15 mm). As the estuary widens near its mouth the currents decelerate and the coarser fraction of the sediment load deposits on the bed. This results in the development of extensive mouth bars and middle bars (Figure 2-12). The continuous growth of these bars forces the flow in the Meghna sideways, resulting in erosion of both the east and west riverbanks.

2.4 Micro-scale development

The micro-scale concerns the drainage of and within polders and peripheral rivers (connecting the polders to the larger tidal channels) and bank erosion. The polders were originally designed in such a way that embankments, sluices and gates prohibit the inflow of salt water and regulating the inflow of fresh water, while allowing the outflow of excess rainwater. These original constructions have fallen in disrepair for a large number of reasons (from socio-economic to physical) that vary among the various polders. A detailed account of the mechanisms responsible for the loss of drainage per polder is beyond the scope of this report. Instead, this report focusses on generic mechanisms related to drainage and to bank erosion which are coupled to the overall dynamics of the delta (as described in section 2.1 - 2.3). The description below also includes Tidal River Management (TRM) because it is already applied in the southwestern delta to mitigate water logging and navigability of the peripheral rivers. Aspects covered below include

- Water logging of polders
- High water levels
- Bank erosion

2.4.1 Water logging of polders

Waterlogging is the flooding of polders during periods of high rainfall (Figure 2-19). When the polders were constructed, the bed level within the polders was higher than the bed level of the channels outside the polders, and rainwater flows out of the polder upon opening the sluice gates. A large number of polders in the southwest tidally-dominated delta presently suffers from drainage problems during high rainfall events (increased flooding frequency in Figure 2-12). There are a number of reasons why the drainage capacity has been reduced: (1) a loss in relative elevation, (2) loss of drainage capacity with the khals (canals within the polders) and around the regulators, and (3) a change in tidal dynamics and silting up of the peripheral rivers. These aspects will be discussed in more detail below.

Figure 2-19 Waterlogging along the Hari river. Source: IWM.

Relative elevation

The polder regions suffering from water logging subside at rates of 3 – 6 mm/yr (compare Figure 2-5 with Figure 2-12). On top of this, the average sea level rises 3 mm/yr, resulting in a relative sea level rise of 6 – 9 mm/yr. Over a period of 60 years this amounts to 36 – 54 cm. Before construction of the polders, most of the area was already low-lying, with bed levels slightly below high tide levels (probably several dm below HW, as in the present-day Sundarbans). As a result of sea level rise and subsidence, the bed level in the polders is now approaching mean sea level. Under perfect drainage conditions, the polders that were historically able to drain their excess water throughout the tidal cycle, can now only drain during half of the tidal cycle.

Loss of drainage channel capacity

Water flows in and out of the polders through the sluices and the khals. Both the khals and regulators are poorly maintained. Therefore, many of the khals and the area around the regulators silted up (Figure 2-20), and sluice gates became dysfunctional over time. Additionally, the flow through the khals was disrupted by small-scale local interventions aiming to use the khals to store water. As a combined result, the flow conveyance has been substantially reduced, lowering the internal drainage capacity of the polders

Figure 2-20 Siltation near a regulator in the Hari river. Source: IWM.

Infilling of peripheral rivers and tidal amplification

In some of the landwards located polders, the drainage is further disrupted because of morphological processes. The peripheral rivers connecting the polders to the larger tidal channels silted up (Figure 2-21) because of the high sediment availability and loss of tidal flow. Before polder construction, the regular inundation of the land provided a tidal flow that formed and maintained these peripheral channels. After construction of the embankments, the reduction of flow velocities and large availability of fine-grained sediment led to infilling of the peripheral rivers. As a result of the higher bed levels, tidal low water levels increased, and the polders are no longer able to naturally drain excess water (especially in combination with sea level rise and subsidence).

Figure 2-21 Infilling of the old Passur river near Bothiaghata, Khulna, in 2010 (left) and the Chitra river in Teokhada, Khulna, in 2011 (right). Source: IWM.

In addition, the highwater levels increased due to tidal amplification (see Figure 2-8 and LTMRA-18, 2020). This increase in highwater levels enables transport of turbid waters through the peripheral rivers at heights exceeding the height of the original polders. As a result, the bed level of the peripheral rivers at a certain point may exceed the bed level within the polders.

2.4.2 Highwater levels

Cyclones generate storm surges of several meters (see also section 2.3.1). Using historical cyclones from the period 1960 – 2020 (Figure 2-10), the highwater levels along the 5 selected polders have been computed (Figure 2-22). Storm surge levels may be as high as 6 meters in the northeast of the Bay of Bengal (polder 59/2 in the Meghna estuary and polders 64/1a and 64/1b south of Chittagong). Storm surge levels are much lower for polders located more landward, with levels of 3-3.5 meter in polders 15 and 29.

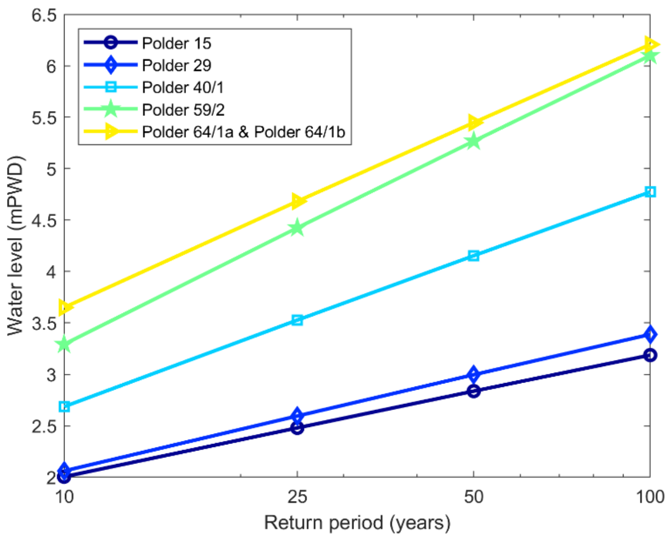

Figure 2-22 Extreme water levels along the 5 selected polders for a return interval of 10 to 100 years, for present conditions. Based on LTMRA-49

Highwater levels during non-storm conditions have been increasing in the past decades because of tidal amplification and an increase in relative SLR. Amplification of tides along the main distributaries in the southwest delta has resulted in an increase in highwater levels of 1.5 meter in the past 60 years, while the mean sea levels increased around 0.5 meter (Section 2.3). In total, highwaters therefore increased up to 2 meters. This increase has been almost linear in time and will therefore continue in the near future. This has provided a substantial increase in flood risks in the polders since their original construction in the 1960's (Adnan et al., 2019). Note that this tidally-induced increase in highwater levels is comparable to the difference in storm surges between a storm with a recurrence interval of 10 years and one with a recurrence interval of 100 years.

The tidal range in the peripheral channels has significantly declined due to their infill with fine-grained sediments. Revitalizing these peripheral channels through TRM may lead to increasing high tidal water levels, especially in peripheral rivers that nearly completed silted up

2.4.3 Bank erosion

The embankments of the polders in the GBM delta are located along the Bay of Bengal, along primary distributaries (such as the Passur, Sibsa, or Baleshwar) or along peripheral rivers. The embankments directly exposed to the Bay of Bengal have experienced relatively minor hydrodynamic changes, only related to relative sea level rise (and bank erosion when constructed along an already eroding coastal stretch). Most bank erosion takes place along the various tidal channels. Bank erosion along such tidal channels is a natural, widely occurring phenomenon in alluvial deltas due to lateral channel migration. In order to understand the risk of bank erosion to polder embankments, it is necessary to differentiate between riverbank erosion along primary distributaries, connecting rivers, and blind peripheral rivers. Bank erosion along the primary distributaries and along the connecting rivers has been discussed in section 2.3.3. This section elaborates on bank erosion along blind peripheral rivers and the impact of bank erosion on polders.

Bank erosion along the main channels is partly the result of lateral migration, and partly because of human interventions. As visualized in Figure 2-14, polders 56/7 and 59/2 along the Meghna estuary erode at large rates, up to 300 m/yr. Also polder 73/1 experiences erosion (see Figure 2-12). The vulnerability of the polders along the other main distributaries can be assessed from Figure 2-15. In the Sibsa, only polder 32 suffers from limited bank erosion resulting from lateral migration (Figure 2-15a). In the Passur, the large part of polder 35/2 experiences substantial bank erosion (up to 15 m/yr; Figure 2-15b); polder 34/2 limitedly erodes between km 500 and 515. As elaborated in van

Maren et al. (2022), the bank erosion along the Sibsa river and the upper Passur / Rupsha river is strongly influenced by the construction of the polders. In the Baleswar, the west bank erodes along the southern reaches of polder 35/1. All polders along the west bank experience bank erosion, sometimes along stretches 20 km long. Peak erosion rates are 20 m/yr (polder 40/1 and 40/2). Bank erosion around polder 39/1 and 39/2 results from channel expansion, whereas the large erosion rates in polder 40/1 and 40/2 result from lateral migration of the large meander belts. All polders along the Bishkali suffer from local bank erosion, typically over stretches of ~5 km in length.

Bank erosion also takes place along the rivers connecting the Passur and Sibsa rivers. Polder 32 (see also Figure 2-17) is squeezed in-between the eroding Sutarkhali and Dhaki rivers (and the Sibsa river). Polder 33, on the other side of the Sutarkhali experiences erosion from these connecting rivers as well. Polder 31 is located in-between the Badupgacha and Dhaki rivers, and therefore also suffers from bank erosion. Bank erosion takes place along the southern borders of polders 22 and 30 (along the Badupgacha river), but less from their eastern western, and northern boundaries. Polder 29 experiences erosion locally, at the confluence of the Bhadra river with the Hari river (Figure 2-23).

Figure 2-23 river bank erosion along the Bhadra river (left) resulting in flooding of agricultural land (right – see Bhadra river in the background). Photos taken during a field visit in 2019.

3 Future development: climate change and human interventions

The future development of the delta is regulated by hydrodynamic and sedimentary processes that shaped the historic development (as described in the previous chapter) but also by climatic and human-induced changes. The most important climate change impacts are sea level rise, changes in storm frequency / intensity and river discharge / sediment load. Human interventions include large-scale construction works (such as upstream reservoirs or large-scale reclamation schemes) but also small-scale, local interventions. But while large-scale interventions require long-term planning and are therefore reasonably known for the coming decades, the timelines of small-scale interventions are much shorter and therefore only limitedly predictable. On top of the long-term delta development and these climatic and human-induced changes, the system is also still responding to earlier interventions, i.e. the system is not in equilibrium. An example is the tidal amplification in the polder region illustrated with the Passur – Sibsa estuary.

The purpose of this chapter is to provide an overview of climate change and anthropogenic pressures (section 3.1) and their impact (section 3.2).

3.1 Climate change and anthropogenic pressures

3.1.1 Climate change scenarios

Climate change scenarios are based on the sixth IPCC report (IPCC, 2019) using the RCP8.5 scenario (Business as usual, i.e. extrapolating the present-day increase in the current CO_2 emissions) and the RCP4.5 scenario (stabilizing anthropogenic emissions, i.e. CO_2 emissions remain close to the present-day emissions). These scenarios include projections for sea level rise and for a change in precipitation. In 2050 the sea level is projected to increase to 0.18 m (RCP4.5) to 0.22 m (RCP8.5) for the median likeliness per scenario; sea levels increase to 0.49 (RCP4.5) to 0.76 m (RCP8.5) in 2100. However, the spread in predictions is also large, as visualized in Figure 3-1.

Precipitation and temperature changes are based on the outcome of 4 global models (GFDLESM2M, HadGEM2, MIROC-ESM-CHEM, and NORESM-M). Averaging the outcome of these models and RCP scenarios suggests that the temperature will increase with 1.7°C (Ganges basin) to 2.1°C (Brahmaputra basin) in 2040 to 3.5°C (Ganges basin) to 4.0°C (Brahmaputra basin) in 2040 (LTMRA-45, 2021). And although the absolute values of precipitation change may vary among the different global climate models, their trend is quite consistent. The precipitation change is initially very limited (a decrease of less than 1% by 2040). By 2080, the precipitation is predicted to increase with approximately 10% (LTMRA-45, 2021). The largest precipitation increase is during the pre-monsoon (up to 25%) while the monsoon and post-monsoon precipitation change is comparable to the annual average. The winters will become drier than today. This will lead to lower direct availability of fresh water through precipitation and fluvial supply, and hence a higher. This will increase groundwater extraction which will in turn aggravate subsidence resulting from groundwater extraction.

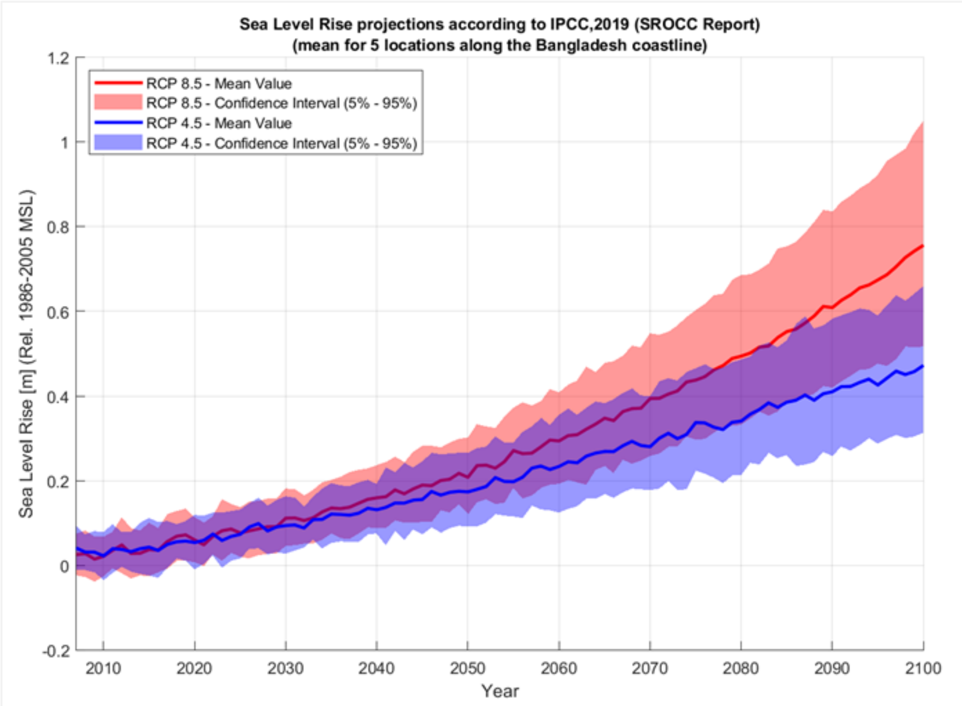

Figure 3-1 Sea level rise projection for the Northern Bay of Bengal for the RCP8.5 scenario (Business as usual) and RCP4.5 scenario (stabilizing anthropogenic emissions). From LTMRA-45 (2021)

The precipitation is also projected to increase in the river basins of the Ganges and Brahmaputra, influencing their river discharge and sediment load. A catchment model (HydroTrend) is therefore used to compute changes in river discharge and sediment load for each of the global climate models and subsequently averaged to obtain a best estimate for changes in river discharge and sediment load (Eckland et al., in prep.). By 2100, the average river discharge in the Ganges river is projected to increase with 34% under the RCP4.5 scenario and 44% under the RCP8.5 scenario. The average discharge of the Brahmaputra river increases with 19% under the RCP4.5 scenario and 27% under the RCP8.5 scenario. The discharge of both rivers combined increases with 25% and 33% for the RCP4.5 and RCP8.5 scenarios, respectively. Sediment fluxes are computed as well based on precipitation, bed level gradients and a spatially varying surface erodibility based on land use and geology. Surface erosion rates increase non-linearly with rainfall, and therefore the sediment fluxes in the Ganges and Brahmaputra rivers increase more strongly than the discharge. For RCP4.5 (RCP8.5) the sediment load in the Ganges river increases with 27% (42%), in the Brahmaputra river with 39% (66%), totalling 34% (55%).

Tropical cyclones are important for flooding and wave overtopping during storm surges. Climate change will probably lead to a shift towards more severe storms, resulting in a reduction of moderate cyclones and an increase in severe cyclones (Knutson et al., 2020, 2021; LTMRA-45). The low-category cyclones (category 0 on the Saffir–Simpson intensity scale) may even decrease in frequency, whereas cyclones with a category 3-5 will become increasingly more likely (~20%, see LTMRA-45 (2021) and references therein). An increase in temperature of 4º (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., submitted). An increase of cyclonic wind speeds of 8% is used to predict the impact of climate change on storm surges as part of the LTM project.

3.1.2 Human interventions

A number of large interventions are scheduled in the Ganges – Brahmaputra basin that influence the delta. Important potential interventions include the Indian National river Linking project (NRLP), the Ganges barrage, and restoration of the Gorai river.

Indian National river Linking project (NRLP)

The Indian National river Linking Project (NRLP) is a large-scale civil engineering project to connect various rivers through canals to expand agricultural production and address water scarcity (Higgins et al., 2018). Numerous dams, reservoirs, and canals are planned that will store and redistribute water to reduce temporal and spatial inconsistencies in supply. The NRLP is expected to have significant effects on the water and sediment supply to the GBM delta through three fundamental processes; (1) increases in reservoir trapping, (2) storage of high flow during the monsoon, and release during the dry season, (3) decrease of the average discharge due to increased water utilization. Higgins et al. (2018) compiled a complete database on proposed interventions within the NRLP and estimated the potential changes the interventions will have on the mean monthly water discharge and sediment load towards the GBM delta (Ganges and Brahmaputra rivers). The Brahmaputra is expected to show a relatively small decrease of 6% in the mean annual river discharge. However, as most of the NRLP interventions are planned in the Ganges basin, the mean annual discharge of this river is estimated to show a large decrease of 24%. The range in the reduction in sediment load associated to the NRLP is estimated by use of the lower and upper bounds of existing sediment rating curves and is estimated to be in the range of -9% - - 25% (Brahmaputra) and -39% - -75% (Ganges).

Ganges Barrage

The Ganges barrage was for a prolonged period of time considered a means to store water from the Ganges in the wet season, and to distribute this to the delta in the dry season. This would reduce salinization issues in the delta, especially in the southwest. The benefits of the Ganges Barrage are (Alam et al., 2018): (i) to harness properly the benefits of the Ganges Water Treaty 1996 (ii) to save the Sundarbans and the south-west region of the country from salinity intrusion and (iii) to utilize the surface water instead of groundwater which is contaminated with arsenic. It is unclear whether the Ganges barrage project will ever be realised. The Ganges barrage will raise water levels in the Bangladesh part of the Ganges, thereby allowing flow from the Ganges to the Bay of Bengal through some of its abandoned distributaries or distributaries suffering from low flow rates (notably the Gorai river). The height to which the water levels will increase and over what part of the year are not available, and therefore only estimates exist on the increase of freshwater flow through the Gorai river as a result of the Ganges Barrage.

Gorai restoration

The Gorai river is the most important distributary of the Ganges flowing into the Delta. The Gorai received approximately 10-20% of the Ganges river flow, but this has declined due to the construction of the Farakka barrage. The Farakka barrage especially influences river flow in the Ganges during the dry season, leading to a considerable reduction of low flow rates and water levels. During low water levels, the Ganges water cannot flow into the Gorai river and the Gorai dries up. In addition to these low water levels, the morphology of the offtake area has also considerably changed: large amounts of sediment deposited around the area diversion point of the Gorai. This sediment deposition may be influenced by the reduction of the river discharge (by Farakka barrage), but also by the natural channel dynamics (with a southward encroaching outer bend 6 km upstream of the offtake creating a sheltered zoned near the offtake where sediments deposit). The purpose of the Gorai restoration (by dredging of the Gorai river, but also redesigning the offtake) is to increase the river discharge to the Gorai river in the dry season.

Tidal river management

A solution to water logging is tidal river management (TRM). TRM is a re-introduction of the tidal regime in a polder by creating 1 or more openings in the dikes (Gain et al., 2017). The turbid waters entering the polders deposit sediments, raising the polder elevation. Furthermore, the increase in tidal prism leads to a scouring of the peripheral river, which in turn increases tidal amplitudes. With increasing amplitude, the tidal prism entering the polder becomes larger, accelerating the depositional processes in the polder. On top of that, the increased tidal range leads to a reduction in the low water level in the peripheral river allowing more drainage. After TRM is completed, the bed levels in the polders have been raised whereas low water levels in the peripheral rivers have lowered, leading to more efficient water drainage and thereby solving water logging problems in the polders.

Three TRM's have been executed in the Sibsa basin (Gain et al., 2017): in Beel Bhania 600 ha, 1997-2001), in Beel Khuksia (1100 ha, in 2006-2012), and Beel Pakimara (700 ha, since 2015 – see photos in Figure 3-2). Both Beel Bhania and Khuksia were located on the Hari river, which eroded from a bed level of -1 m to -10 m, and widened by a factor 2-3. Around 6.5 million m^3 of sediment was deposited in Beel Bhania (Gain et al., 2017) and the thickness of deposits varied between 0.2 and 2 meters. An important indicator for success of TRM is the extent to which the sediment is evenly distributed within the polder: most sediment tends to deposit close to the entrance, leading to waterlogging issues (as especially experienced in Beel Khuksia).

Figure 3-2 TRM in beel Pakimara: flooded land (left) and eroding embankments along the river draining into the polder. Photos taken during a field visit in 2019.

TRM became institutionalized since 1997, when the Bangladesh Water Development Board flooded a low-lying congested polder (Amir and Khan, 2019). But even though TRM has the potential to substantially reduce flood risks (Adnan et al., 2020) it is only limitedly applied. This is partly because of complex socio-economic issues (compensation and relocation of polder inhabitants) but also because of the varying degree of success of TRM practice (Gain et al., 2017, Adnan et al., 2020). As a consequence, there is a need to better predict the impact of TRM. The spatial extent of the sediment deposits needs to be adequately predicted and optimized through strategic opening of embankments (Islam et al., 2021).

Optimization of sediment deposition during TRM by varying the various openings/ breaches has been evaluated for Beel by LTMRA-64. Sedimentation rates during a historic TRM operation were first hindcasted and subsequently optimized. Key for spatially uniform sediment deposits is that the embankments should be breached at multiple locations, and at locations where khals exist or a tidal channel existed before polder construction which needs to be excavated prior to polder opening.

Local interventions

A large number of local interventions are constantly executed throughout the delta, varying from local hydraulic engineering (construction of e.g. jetties and groins) to agricultural (a shift from rice cultivation to aquaculture). These interventions typically influence local hydrodynamics and sediment dynamics, but not on a larger scale. Even more, such local interventions require less planning, are often not centrally organized or registered, and therefore not known in advance. As part of this large-scale assessments of delta dynamics, we do therefore not account for local interventions.

Closure of connecting rivers in the Passur-Sibsa system

An important outcome of LTMRA-18 was that an important mechanism driving bank erosion tidal amplification and shoaling of the Passur river is conveyance of tidal flow between the Passur and Sibsa rivers. A potential solution alleviating erosion, flooding and shoaling issues is therefore to close the channels connecting both systems.

Cross-dams in the Meghna estuary

Cross-dams limit tidal exchange and may trap sediments, when strategically placed. Cross-dams are therefore considered in the mouth of the Meghna estuary to trap sediments and gain land. These cross-dams may be placed between the mainland and two large natural islands (Shawna whip and Urir char; cross-dam 1 and cross-dam 2 in Figure 3-3).

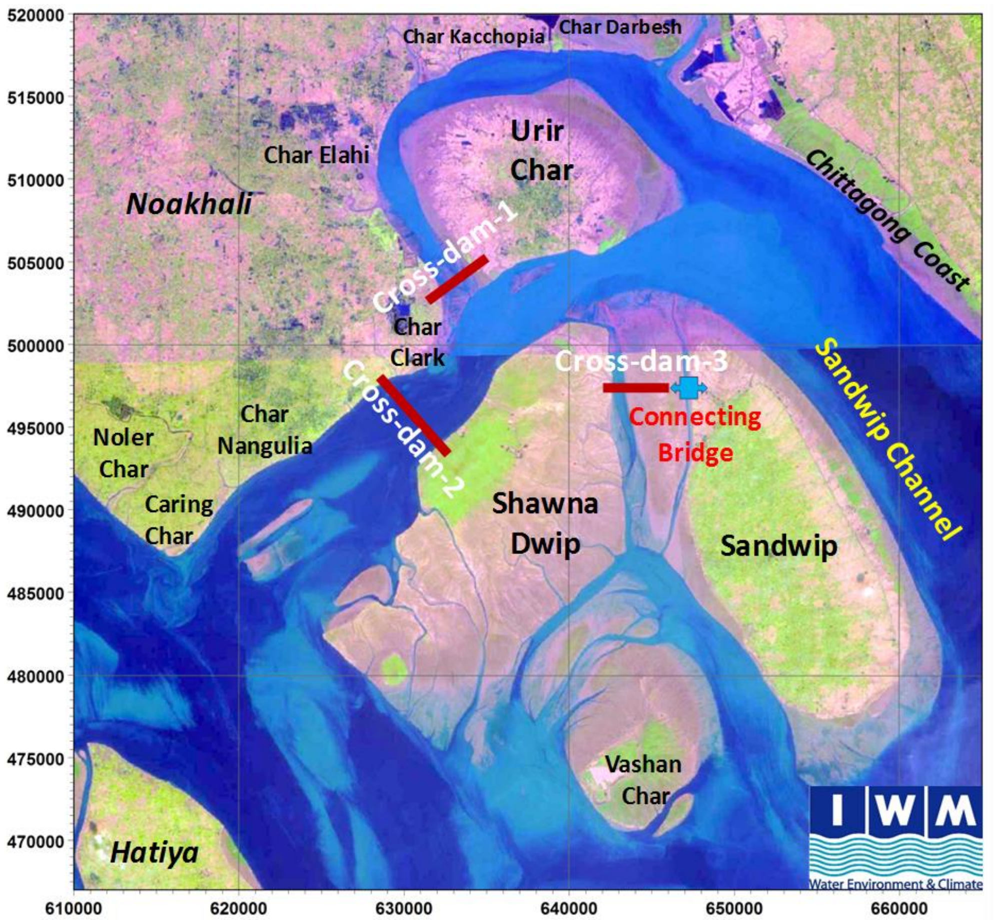

Figure 3-3 Cross-dams in the Meghna estuary

Mangrove restoration

Mangroves provide many ecosystem services, such as coastal protection, damping of tidal waves, nurseries for fish, timber production, sequestration of carbon, and water quality improvement.

Mangroves are now primarily restored locally (on a polder level) to prevent flooding (such as through the ECOBAS project) or to improve the quality of aquaculture ponds (Rahman et al., 2020). Upscaling of mangrove restoration will partly restore the pristine dynamics of the delta by dissipating tidal energy (leading to a reduction of the tidal range) and storm surge waves, as well as allowing the delta to grow with sea level rise. Upscaling is not yet realistically considered as a potential useful intervention, but this may change in view of anticipated climate change. The potential of large-scale restoration is illustrated by Gijón Mancheño et al. (2021).

3.1.3 Subsidence

The observed historic subsidence rates (Figure 2-5) are assumed to remain unchanged in the future. The spatial subsidence map is input for the macro-scale and micro-scale models; for individual polders the subsidence rates in Table 3-1 are used.

Table 3-1 : Land subsidence rate in the coastal zone of Bangladesh

Polder	Region	Land Subsidence (mm/yr)
15	South-West	5
29	South-West	4
40/1	South-West	6
59/2	South-East	4.7
64/1a	Eastern Hilly	2
64/1b	Eastern Hilly	2

3.2 Impact of climate change and human interventions

3.2.1 Climate change

Extreme water levels

Extreme water levels are a combination of the mean water level, the tidal amplitude, and the storm surge height. The mean sea level follows directly from the RCP scenarios. Changes in tidal dynamics are computed with the 1D macro-scale model, while changes in storm surge height are computed with the storm surge model. Both results will be evaluated below.

Sea level rise and changes in the discharge regime influences tidal propagation in the various distributaries. The impact of climate change has been investigated with the 1D macro-scale model (LTMRA-34) using the following climate change scenarios:

- S1: sea level rise using the 50% median prediction of RCP4.5 and RCP 8.5 (31 and 76 cm, resp.) in combination with change in river discharge as predicted by the HydroTrend model.
- S2: as S1, but with the 5% upper bound prediction of RCP4.5 and RCP8.5 (47 and 105 cm, resp.)

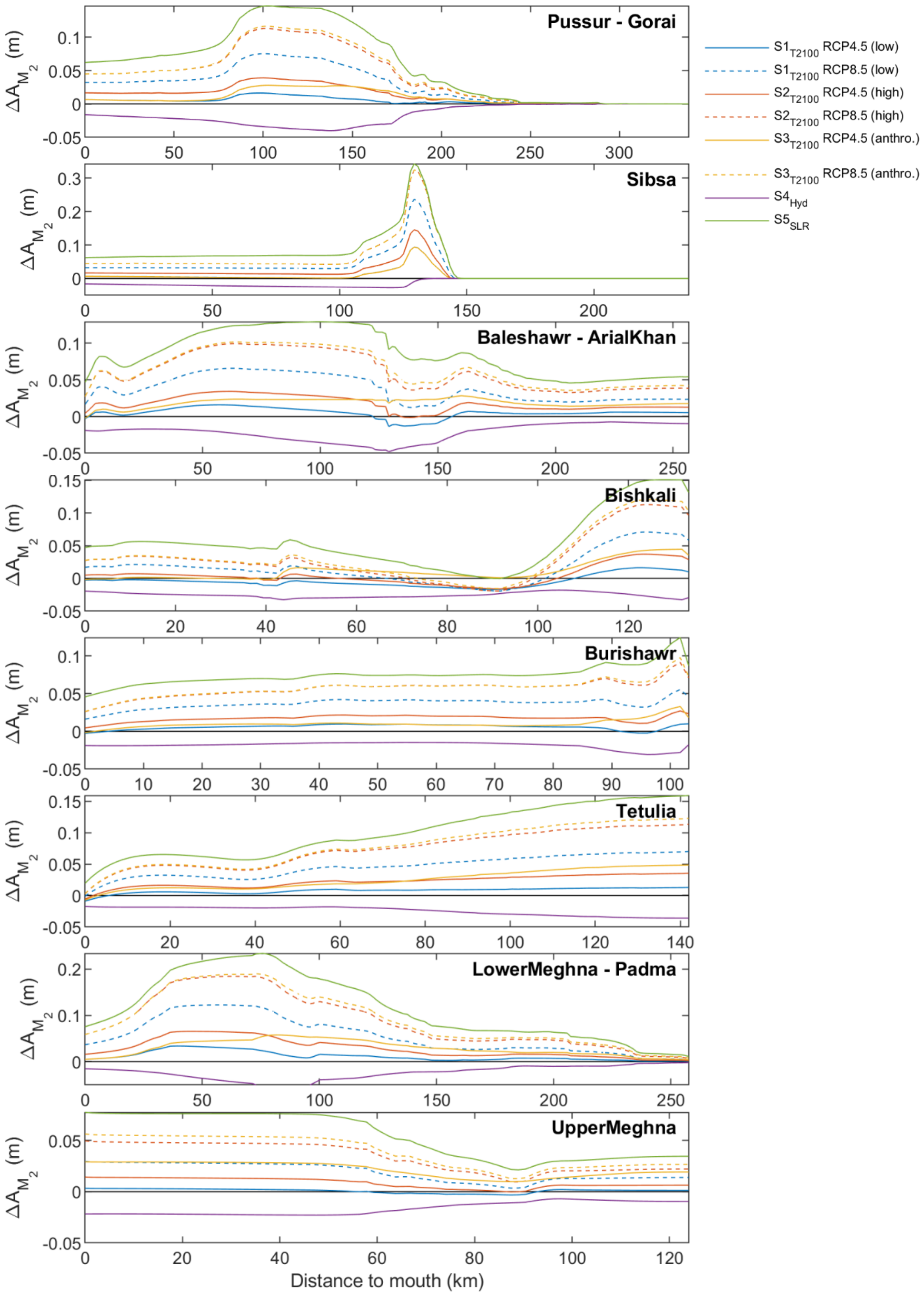

Figure 3-4 Change in the M_2 tidal amplitude (m) with respect to the reference scenario. From LTMRA-34

Depending on the river system, the location within each river, and the considered scenario, the M2 tidal amplitude increases up to 30 cm; the highest increase in tidal amplitude is predicted for the Sibsa and Meghna rivers (Figure 3-4). Overall, the increase in M2 amplitude is between 10 and 20 cm. M2 is the largest tidal constituent in the GBM delta, and its amplitude change is about half of the total tidal range change. Amplification of the total tidal range will therefore be in the order of several dm. This means that in areas where the increase in M2 amplitude is 10 cm for relative sea level rise of 105 cm, the total tidal range will increase approximately 20 cm, and the highwater levels will rise approximately 125 cm.

The extreme water levels during storm surges are computed using an 8% increase in wind speed for the year 2050 (20 cm sea level rise). The increase in storm surge height for the various selected polders is 20 to 40 cm for a recurrence interval of 10 years, rising to 45 to 80 cm for a recurrence interval of 100 years (Figure 3-5). This increase in storm surge height is partly resulting from sea level rise (20 cm) – the contribution of only the increase in storm intensity is therefore 0-20 cm to 25-60 cm (for storms with a recurrence interval of 10 and 100 years, resp.).

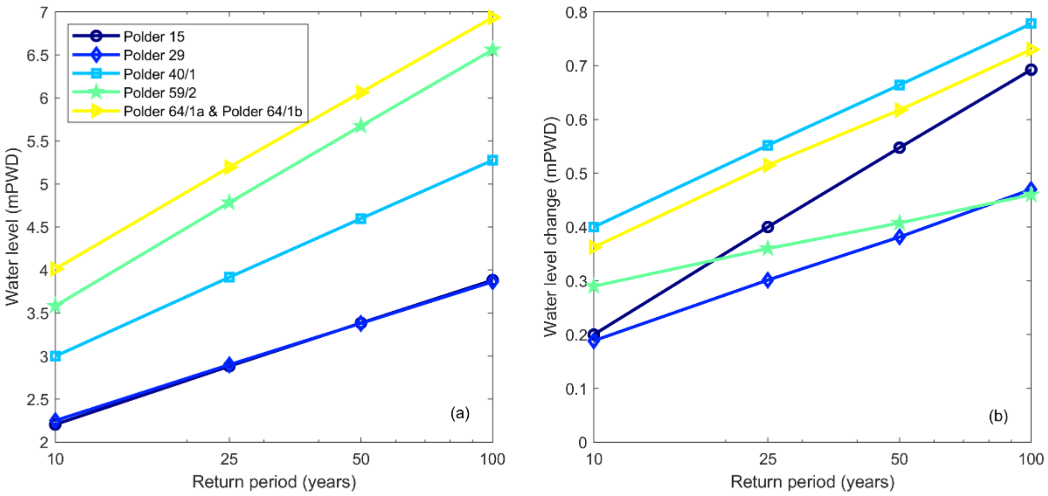

Figure 3-5 Extreme water levels (a) along the 5 selected polders for a return interval of 10 to 100 years, for scenarios including climate change in 2050 (sea level rise as in Figure 3-1, subsidence as in Table 3-1, and an 8% increase in maximum wind speed). Increase in high water levels (b) relative to the present-day conditions (as visualized in Figure 2-22). Based on LTRMA-49.

The total increase in extreme water levels is a combination of mean sea level, tidal range, and storm surge. Climate change-induced increase in extreme water levels is up to 105 cm (5% upper limit of the RCP8.5 scenario in 2100). The storm surge height in the various polders increases with 30 to 60 cm, while tide-induced highwater levels contribute another 10 to 30 cm.

Morphology

Predictions of morphological response to climate change on a basin scale are executed with the 2D macro-scale model (see Figure 3-6 for spatial patterns; Figure 3-7 for timeseries of spatially aggregated development, and Table 3.2 and Table 3.3 for details). SLR = 1 meter corresponds to the 95% curve for the RCP8.5 climate prediction; SLR = 0.5 meter corresponds to the 50% prediction of the RCP4.5 scenario. SLR = 1 meter is therefore an upper bound for sea level rise, 0.5 meter a lower bound. Note that numerical modelling has been executed with a well schematised hydrograph (discharge regime) and waves were not considered.

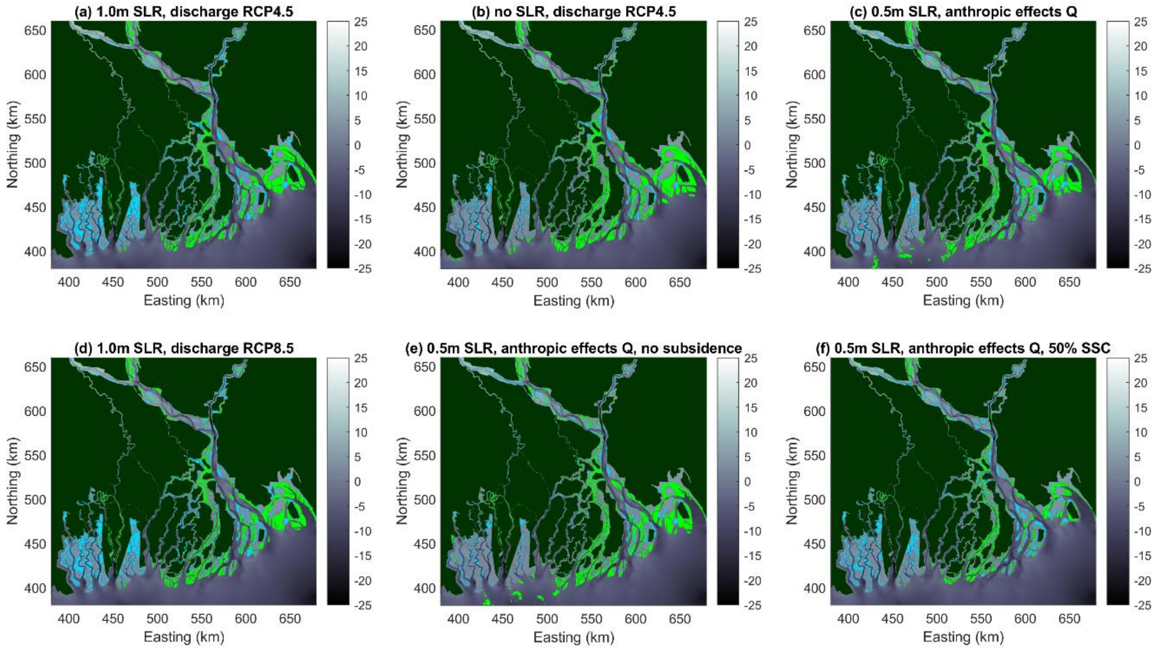

Figure 3-6 Simulated land gain due to sedimentation (green) and loss due to erosion or inundation (blue) for 2090-2100 relative to 2020-2030, for 6 different scenarios. From LTMRA-34

Combining this upper bound for sea level rise with the RCP 8.5 scenario for river discharge (Figure 3-6d) first leads to land gain until 2050, but is followed by a steady net loss of the delta. By 2100 most land gain from the period 2020 – 2050 has disappeared (Figure 3-7). The largest contributor to delta decline is sea level rise, which is demonstrated by the large difference between scenario (a) and (b) (loss of 16 km^2/year for 1 meter sea level rise compared to a net land gain of 22 km^2/year by 2100; see Table 3.3). Subsidence also strongly contributes to the decline, which is demonstrated by the difference between scenario c and e (13 km^2/year by 2100; see Table 3.3). The impact of river discharge changes resulting from RCP 4.5 and 8.5 scenario's is quite small, in the order of 1 km^2/year (compare scenario a and d in Table 3.3). A reduction in the sediment load which may have already happened according to Rahman (2018), also has a major impact, reducing the net gain with 23 km^2/year by 2100 (compare scenario f with scenario c).

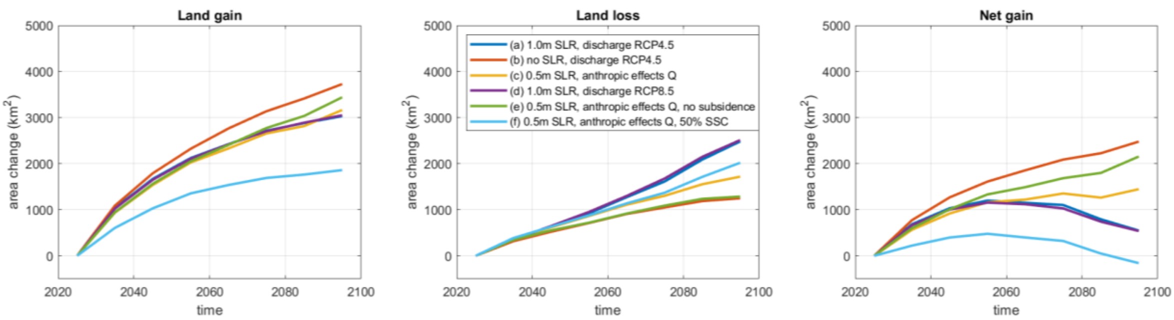

Figure 3-7 Simulated total land gain (km^2) due to sedimentation (left panel), land loss due to erosion and inundation (middle panel), and net land gain (right panel), 2020-2100. From LTMRA-61

All predicted morphological development (Figure 3-6) also displays a pronounced spatial difference reflecting the availability of sediment. The Meghna estuary will be gaining land for most of the scenarios whereas the abandoned southwestern branches are losing land. Sedimentation in the Meghna estuary is limited by the available accommodation space (area where sediments may deposit). Therefore, this area is relatively limitedly impacted by sea level rise. The southwest delta (including the Sundarbans), on the other hand, is supply-limited in the numerical model. This means that the rate of accretion is limited by the amount of sediments that are available. However, a potential shortcoming of the 2D model responsible for these scenario predictions is that the east to west transport of Meghna plume sediments in the Bay of Bengal is quite low whereas stratigraphic surveys suggest that the Sundarbans keep pace with relative sea level rise because sufficient sediment (50-100 million ton/year) is transported from the Meghna estuary to the Sundarbans – see also section 2.3.4. Therefore, the pronounced predicted loss of land in the Sundarbans may be overexaggerated by the model.

Table 3.2 Simulated land loss, land gain and net change in km^2/yr , period 2020-2050 (LTMRA-61)

Scenario	Land gain	Land loss	Net change
	km^2/yr	km^2/yr	km^2/yr
(a) 1.0m SLR, discharge RCP4.5	70.7	30.8	40.0
(b) no SLR, discharge RCP4.5	77.5	23.7	53.7
(c) 0.5m SLR, anthropic effects Q	67.5	28.8	38.7
(d) 1.0m SLR, discharge RCP8.5	70.3	31.8	38.5
(e) 0.5m SLR, anthropic effects Q, no subsidence	68.4	24.0	44.4
(f) 0.5m SLR, anthropic effects Q, 50% SSC	45.2	29.2	15.9

Table 3.3 Simulated land loss, land gain and net change in km^2/yr , period 2050-2100 (LTMRA-61).

Scenario	Land gain	Land loss	Net change
	km^2/yr	km^2/yr	km^2/yr
(a) 1.0m SLR, discharge RCP4.5	22.7	39.0	-16.3
(b) no SLR, discharge RCP4.5	35.1	13.4	21.7
(c) 0.5m SLR, anthropic effects Q	28.5	21.4	7.1
(d) 1.0m SLR, discharge RCP8.5	23.6	39.0	-15.4
(e) 0.5m SLR, anthropic effects Q, no subsidence	34.7	14.2	20.6
(f) 0.5m SLR, anthropic effects Q, 50% SSC	12.7	28.6	-15.9

The impact of climate change on bank erosion rates is small, and much less than autonomous development, for the investigated branches of the delta (LTMRA-67, LTMRA-68, LTMRA-69, and LTMRA-70). This is exemplified for the east bank of the Sibsa Estuary in Figure 3-8. This system shows considerable bank erosion rates (up to 10 m/year, extrapolated to 300 meter up to 2049 - Figure 3-8a). Adding climate change impacts (sea level rise) leads to bank erosion rates only several meters lower (Figure 3-8), which is negligible compared to the total bank erosion rates up to ~300 meter. This same model suggests that the bed level of the Sibsa estuary will rise at approximately the same rate as sea level rise (Figure 3-8c).

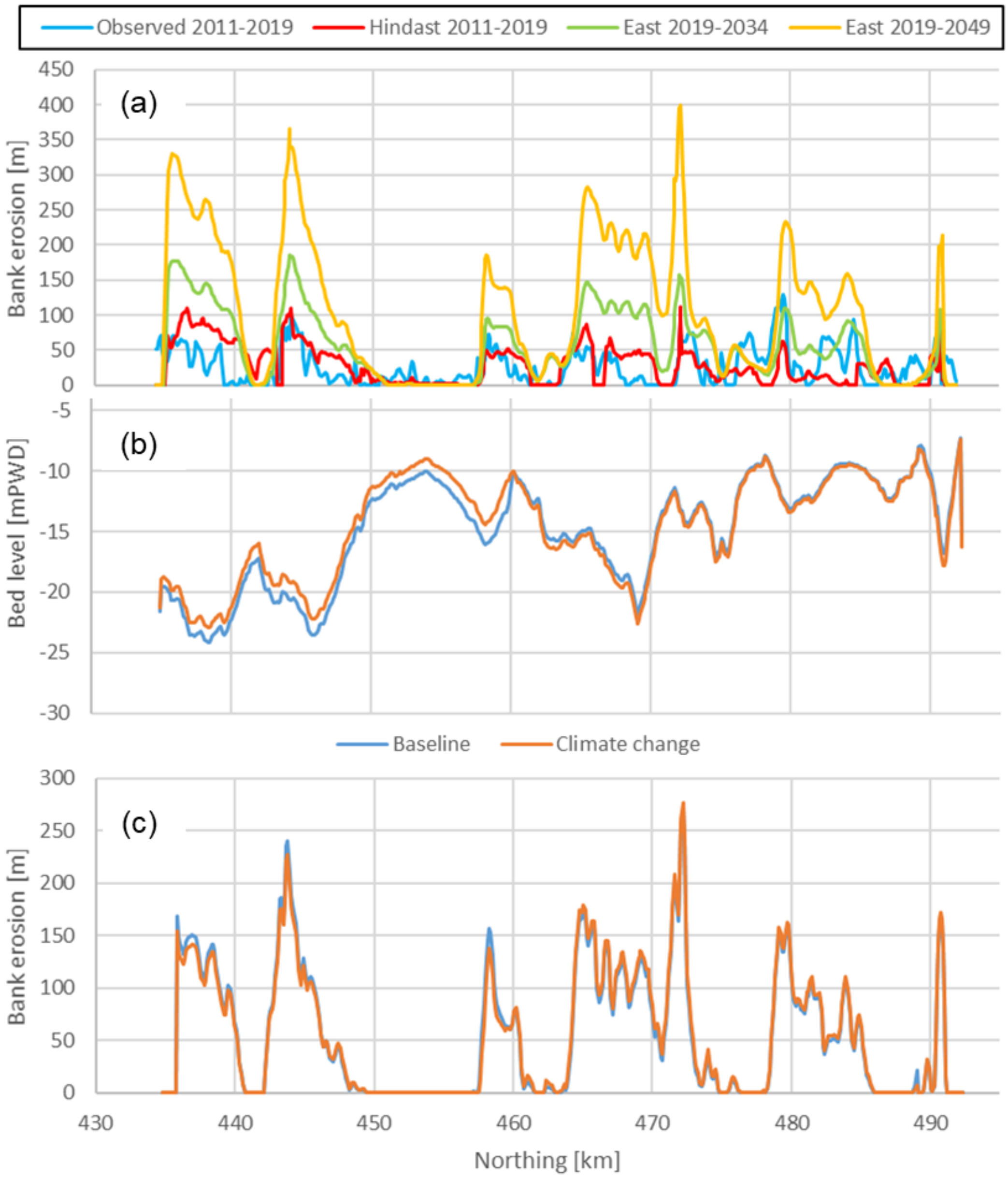

Figure 3-8 Bank erosion (in m) of the east bank of the Sibsa River between 2011 and 2049 (a), and impacts of climate change on bed levels (b) and bank erosion (c)

Salt intrusion

Salt intrusion is influenced by changes of river discharges and especially by SLR due to climate change which causes higher salinity in the estuaries (Figure 3-9). The middle, embanked part of the delta is most impacted by SLR (LTMRA-63). With 92 cm SLR in 2100, freshwater intake will become impossible in the dry season, even for irrigation purposes (2 ppt limit). The 2 ppt limit will shift landward for 76 km in the basins of the Baleshwar, Bishkali, Burishwar and Tetulia rivers (for a SLR of 92 cm). This landward shift is about 16 km in the part of the southwestern delta where salt intrusion was already much more landward because of low freshwater availability (Pasur, Sibsa).

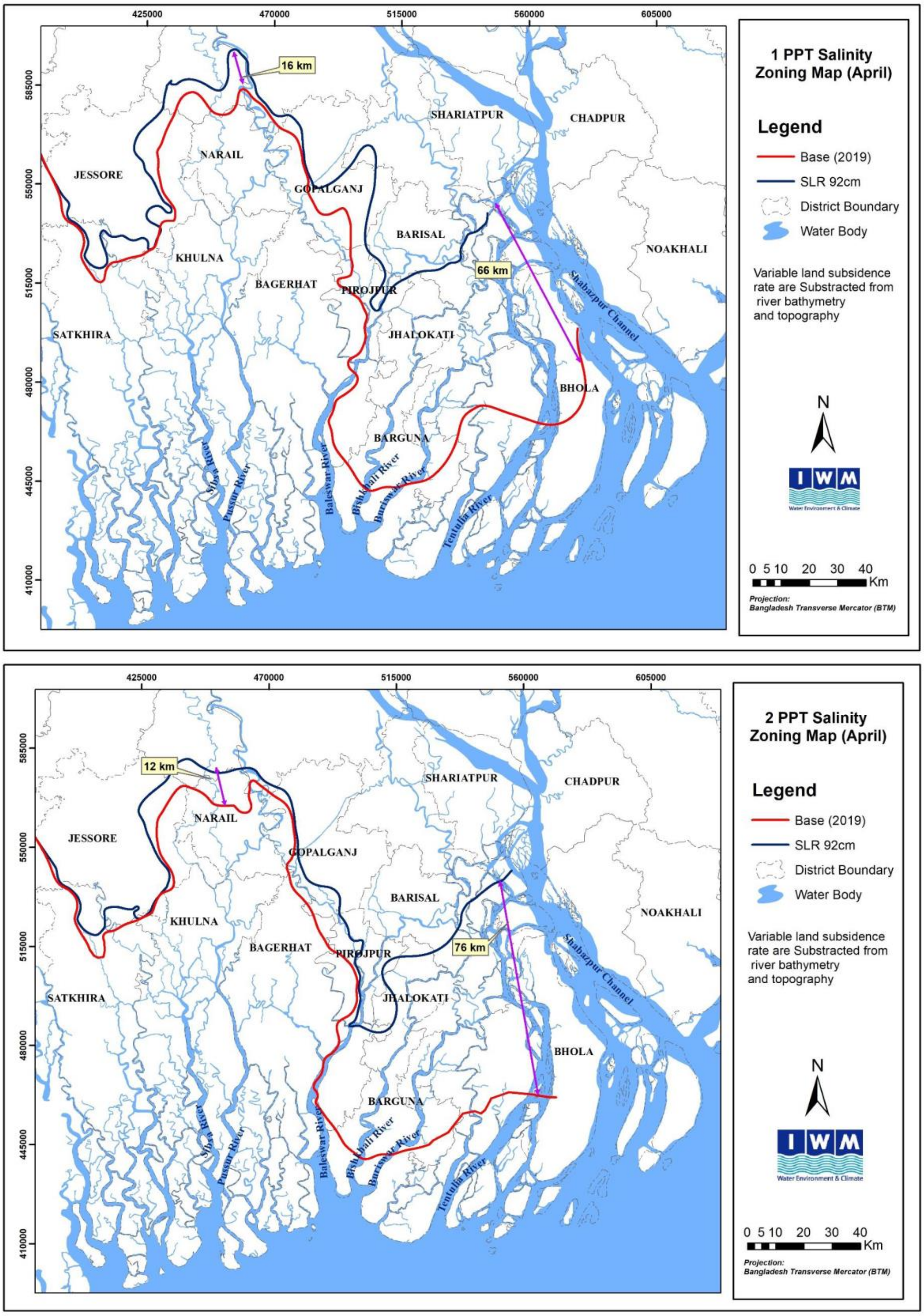

Figure 3-9 Simulated movement of the 1 ppt (upper panel) and 2 ppt (lower panel) salinity line for 92 cm SLR in 2100 (LTMRA-63).

3.2.2 Large-scale interventions

Indian National river Linking project (NRLP)

The exact impact of the NRLP on river discharge and sediment loads is unknown. However, all proposed river diversion schemes will result in a decrease in river discharge and sediment load. Therefore, the macroscale models have been executed with a schematized reduction in discharge and sediment concentration.

The computed morphological evolution is very sensitive to the sediment load (Figure 3-6, Figure 3-7, Table 3.2 and Table 3.3). A 50% reduction of the sediment load leads to a decrease in land of 23 km^2/year over the period 2020-2100 (totalling 1800 km^2 up to the year 2100). Until 2050 this decrease is almost completely the result of a reduction of new land development (99% of the total reduction) but over the period 2050-2100 30% of this reduction is cause by stronger erosion rates of existing land (with 70% of the reduction in land resulting from less new land development).

The reduced river discharge due to the NRLP will increase the salt intrusion, moving the 1 ppt salinity line in the order of 10 km landwards (LTMRA-63).

Ganges Barrage and restoration Gorai

Both the Ganges barrage and the Gorai restoration lead to an increase in the freshwater discharge through the Gorai. Given the lack of details on both schemes, they are both investigated by increasing the river discharge through the Gorai. As such, they are also presented below as a comparable measure.

The Gorai river Restoration Project is meant to augment the dry-season discharge of the river through a combination of a flow divider to divert flows from the Ganges into the Gorai river system supported by initial dredging. Based on in-situ data, depth-averaged modelling of salinity distribution in this system, salinity computation with an analytical model, and comparison with other estuarine systems elsewhere in the world Winterwerp and Giardino (2012) concluded that a river flow of at least 180 m^3/s in the dry-season and at least 1000 m^3/s in the wet-season is required to flush salinity and suspended sediment from the Gorai river, preventing high highwaters and hyper-turbid and anoxic conditions in the river. Salinity modelling (LTMRA-63) shows that implementing the Gorai river restoration or Ganges Barrage project will reduce the salinity intrusion in the Southwest coastal region, and the Ganges Barrage is more effective than the Gorai Restoration project.

The impact of the river flow on tidal dynamics has been investigated with the Delft3D4 Passur – Sibsa model (LTMRA-18) during conditions of high river flow (Figure 3-10a). Increasing the river discharge by restoring Gorai flow conditions will lead to a steady decline of the tidal amplitude, especially upstream of Khulna. Downstream of station SW243, the impact of river flow on tidal amplitudes becomes very small (less than 5 - 10 cm) but with an opposite effect: tidal amplitudes increase with higher Gorai river discharge. This holds for both the Passur and the Sibsa river because of their connectivity. These higher tidal amplitudes (combined with higher water levels induced by the river flow) reduce tidal propagation from the Sibsa river to the Passur river. As a result, an increase in river discharge also leads to higher tidal amplitudes in the Sibsa river (Figure 3-10b).

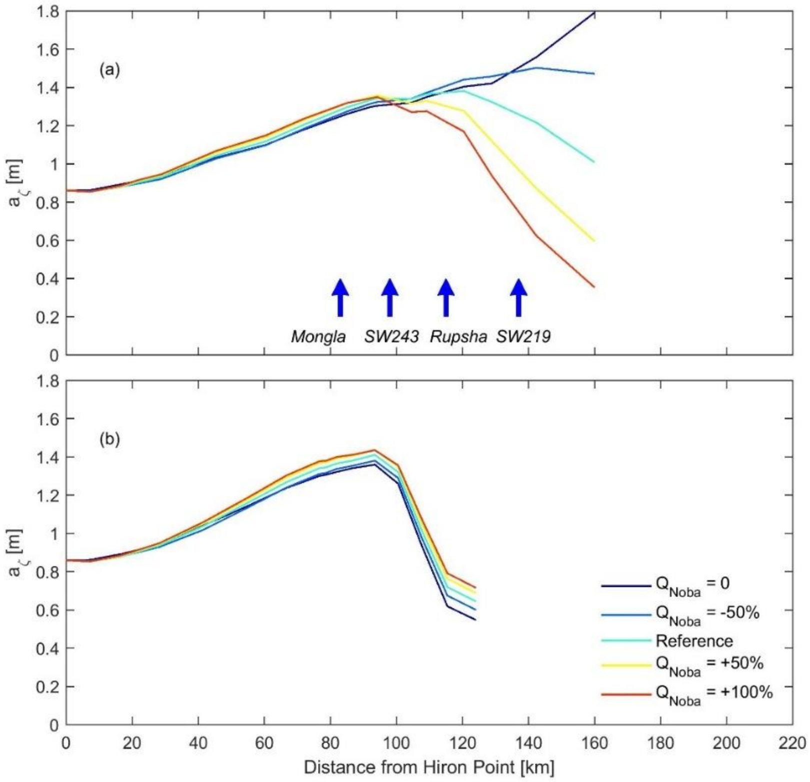

Figure 3-10 Modelled amplitude of the M2 tide in August (during peak discharge conditions) along the thalweg of the Passur / Rupsha river (a) and Sibsa / Hari river (b) for several river discharge conditions from the Nobaganga (no discharge, a 50% lower discharge, the 2011 discharge, a 50% higher discharge, and a 100% higher discharge). From LTMRA-18 (2020)

The effect of an increase in freshwater flow resulting from the Ganges barrage on the morphodynamics of the Passur have been quantified in LTMRA – 29. The increase in freshwater discharge leads to scouring of the riverbed upstream of Mongla. However, because of scouring of these upstream reaches and because of the large sediment load from the Ganges River, the riverbed aggrades seaward of Mongla. The Ganges Barrage project is therefore not beneficial (even more, probably detrimental) for the accessibility of the port of Mongla.

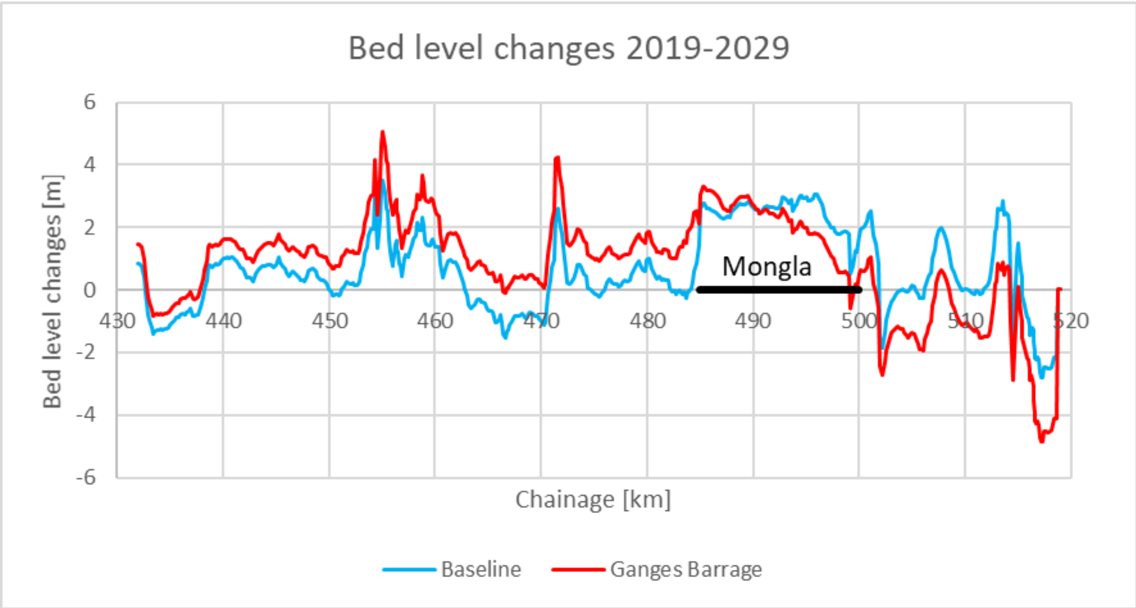

Figure 3-11 Simulated bed level changes 2019-2029 for existing conditions and with Ganges Barrage (X-axis in km Northing). From LTRMA-69.

3.2.3 Meso-scale interventions

Closure of connecting rivers in the Passur-Sibsa system

The connecting rivers convey progressively more water between the Sibsa and the Passur, leading to (1) bank erosion along the connecting rivers, (2) an increase in tidal amplitude in the upper Passur / Rupsha river, (3) shoaling around the port of Mongla, and (4) bank erosion along the lower Sibsa river (van Maren et al., 2022). Predicting such complex morphodynamic responses for a time window exceeding 10 years is beyond the capability of present-day morphodynamic models. However, based on expert judgement it is predicted that the process of flow-capture as now witnessed in the Passur – Sibsa will continue until one or more of the connecting rivers have become the main conveyor of water from the upper Passur river to the sea. River shoaling and bank erosion will therefore likely continue for the coming decades, leading to large loss of land and rendering the port of Mongla inaccessible for large vessels (or requiring excessive dredging volumes).

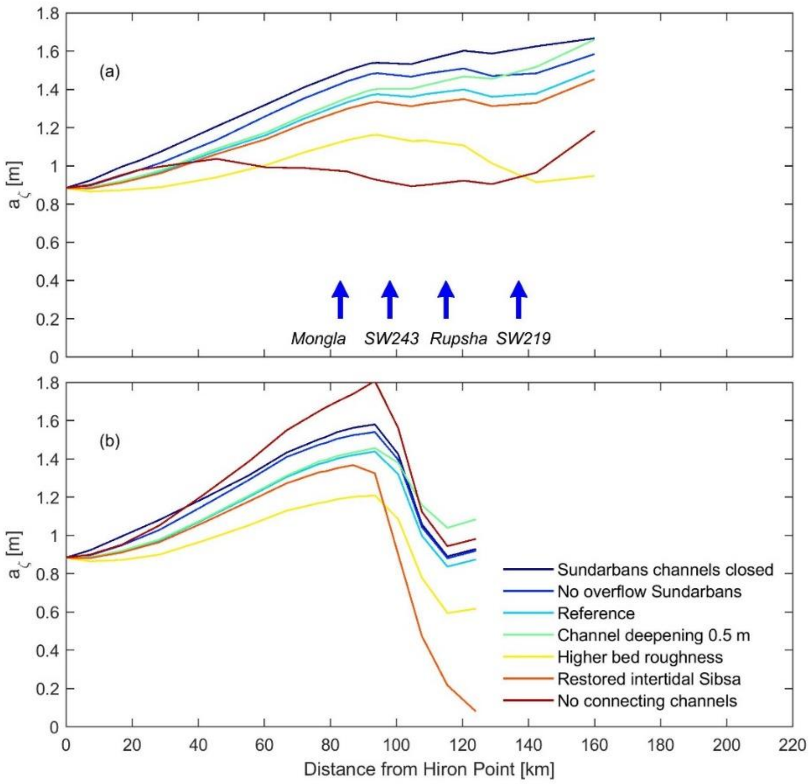

Figure 3-12 Modelled amplitude of the M2 tide in the dry season along the thalweg of the Passur / Rupsha river (a) and Sibsa / Hari river (b) for several model scenarios representing historic developments. From LTMRA-18

The impact of closure of the rivers connecting the Passur and Sibsa rivers in the poldered region has been evaluated with the Delft3D-4 Passur - Sibsa model (LTMRA-18) and the MIKE 21 Passur model (LTMRA-69). Closure of these connecting rivers will lead to a large reduction of the tidal amplitude in the upper Passur river (Figure 3-12), but also to an increase in the tidal range in the smaller rivers draining into the Sibsa river (such as the Hari and Kobadak rivers). Although not explicitly modelled, such closures will completely terminate bank erosion along the connecting rivers and alleviate shoaling in the Passur near Mongla port. Both the Delft3D4 model and the MIKE21 model (scenario D in Figure 3-13) reveal that closure of these connecting channels leads to erosion of the riverbed near Mongla. Erosion of the Mongla riverbed could even be strengthened by allowing flood waters to come in through the Sibsa river, and discharging the tides via the Passur river during the ebb (scenario E in Figure 3-13**).**

However, closure of the existing connecting rivers between the polders may lead to generation of new connecting rivers in the Sundarbans area between Passur and Sibsa. The effects of the generation of such new connecting rivers have not yet been analysed. Therefore, more extended studies are recommended before this intervention is carried out.

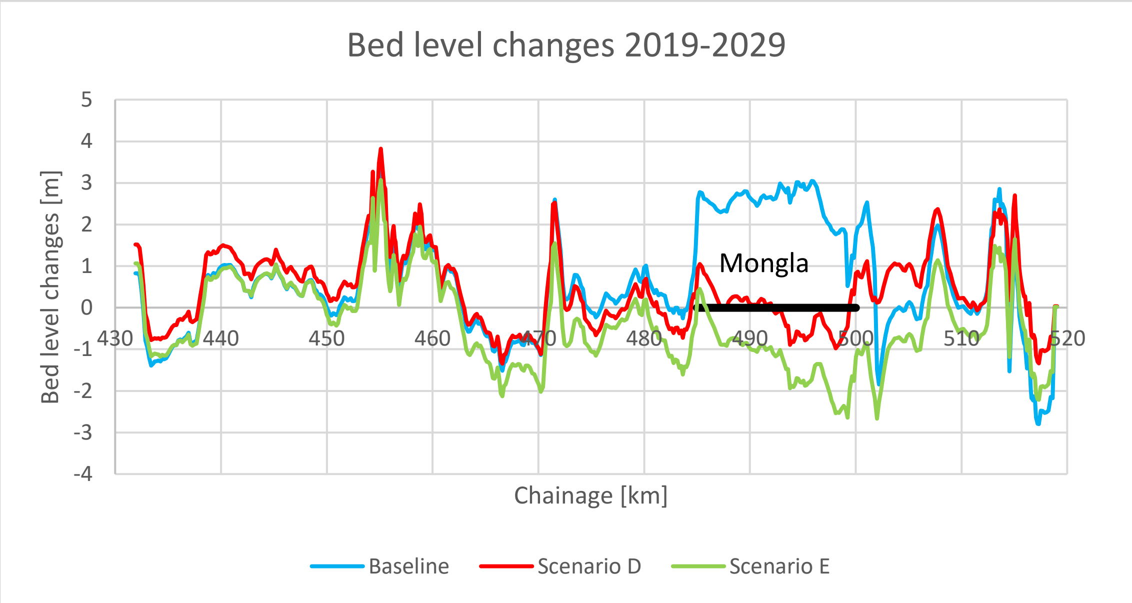

Figure 3-13 Simulated width-integrated bed level changes 2019-2029 for existing conditions, side channels closed (D), and side channels regulated (E).From LTMRA-69.

Cross-dams in the Meghna estuary

Cross-dams in the Meghna estuary are being considered (see Figure 3-3) to trap sediments and thereby create new land. The impact of such cross-dams has been numerically investigated using the Meghna Estuary meso-scale model (Figure 3-14). The model suggests that creation of such cross-dams leads to merging of the Shwarnadwip, Urirchar, and Noakhali and of Sandwip and Bhasan Char. A channel is predicted to develop between Shwarnawhip and Sandwip. Another development is the deepening and widening of the Megna outlet channel, which may lead to erosion of Shwarnadwip and Hatiya Island.

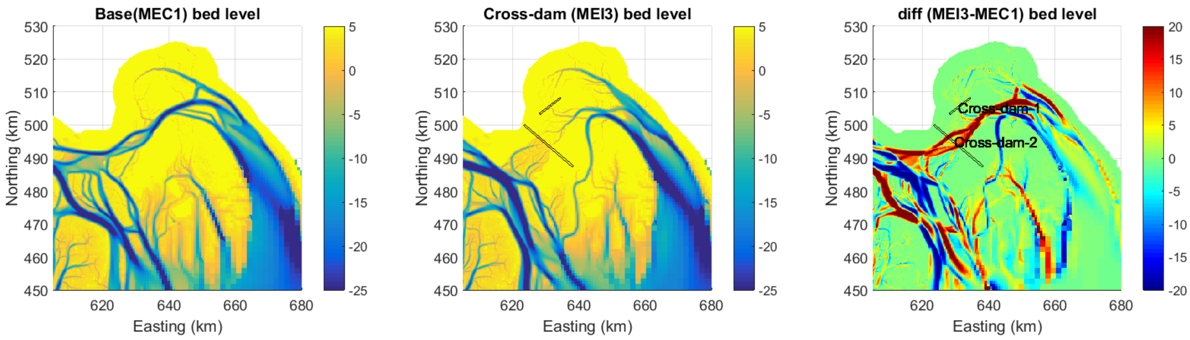

Figure 3-14 Modelled bathymetry in 2050 (with SLR) without (left) and with (middle panel) cross-dams (see Figure 3-3 for location of cross-dams). The right-hand panel provides bed level changes (in meter) clearly showing the infilling of the northern channel. From LTMRA-72).

Smart dredging and disposal

Smart dredging and disposal may alleviate bank erosion rates by providing sufficient cross-sectional space within the rivers to reduce flow velocities near eroding banks. The importance of dredging but also smart disposal of the dredged sediments is illustrated with Figure 3-15 (from LTRMA-68). Removing a large volume of a shoal next to polder 37 in the Baleshwar River (chainage 39-45) alleviates bank erosion rates on the opposite east bank along polder 39/2 with almost 50% (compare scenario A with the reference conditions). However, smart placement of the same dredged material in an adjacent tidal channel has a much bigger impact than only removing the shoal (compare scenario A with B). Erosion rates on the east bank become close to zero, and also erosion rates on the west bank become less.

Even more, dredging a much smaller part of the shoal and by smartly placing the dredged sediment in the nearby channel (scenario C, D) may have a much bigger impact on bank erosion rates than only removed the bed material (scenario A). Smart placement of a dredged volume more than half that of scenario A reduces bank erosion rates along the east bank with 90-95%.

Dredging therefore is a way to mitigate bank erosion, but placement of the dredged material is at least as important as the dredging of the material. Optimal strategies can be designed using numerical models, preferentially in combination with real pilot cases.

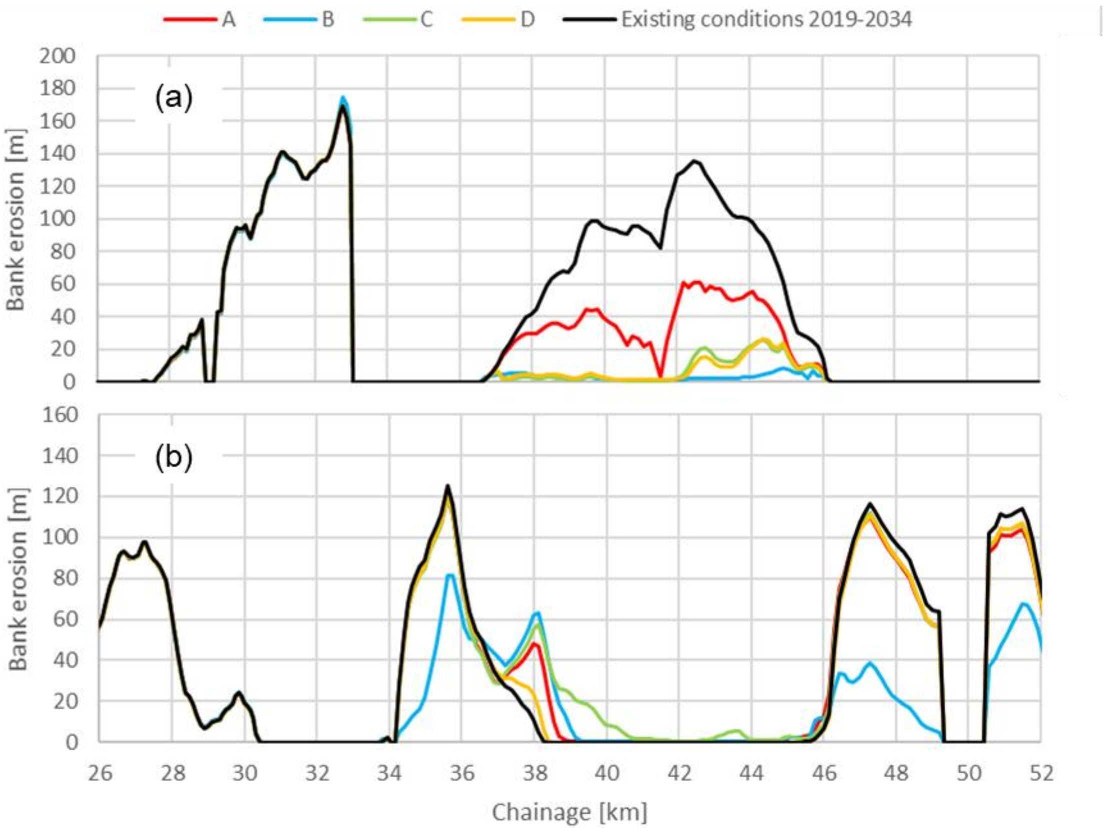

Figure 3-15 Bank erosion rates between 2019 and 2034 along the east (a) and west (b) bank of the Baleshwar river, for reference conditions and dredging scenarios A-D. Scenario A constitutes dredging of 54 million m^3 from a west bank shoal between km 39 and 45, to a depth of 10 meter. Scenario is B is the same as A but with disposal of the dredged material in the adjacent channel (which is causing bank erosion). Scenario C and D are comparable to B but for lower quantities (around 23 million m^3) and differing disposal locations. From LTRMA-68.

Although not experimented with using numerical models, a smart dredging and disposal may also provide a solution for the rapid shoaling of the access channel to Mongla port. Only dredging the approaches to the port will be costly and rather ineffectively because of the connection between the Passur and Sibsa estuary (see section on ‘closure of connecting rivers’ above for details). Dredging requirement have been estimated with the Pussur-Sibsa meso-scale model. This model strongly underestimates sedimentation rates in the Pussur estuary (LTMRA-21). But despite these underestimated siltation rates, the expected annual maintenance dredged rate is 40% of the capital dredging effort (around 4 million m^3 capital dredging; 16 million m^2 maintenance in 10 years) – see LTMRA-72.

A potential solution would be to dredge the Passur estuary and dispose the dredged sediment in the connecting rivers. This sediment placement would reduce the tidal volume flowing through the connecting rivers, and potentially revive flow through the Passur estuary. With increased tidal volumes, the siltation rate near Mongla port would then decrease. In time, this could even set in motion a feedback mechanism where progressively more water is conveyed through the Passur estuary and less through the connecting rivers, at the same time mitigating bank erosion rates in these systems.

Upscaling of TRM

TRM is at present only limitedly executed given the socio-economic impacts, but also because of disappointing results of some historic TRM cases (and failure to understand and predict what the exact impact of TRM is). With accelerating sea level rise and the continued amplification of the tides and subsidence of the polders, it is likely that TRM may need to be upscaled in the future. A question that then arises is to what extent TRM remains effective. More frequent and spatially more extensive TRM execution may lead to a shortage of sediment. Upscaling of TRM in a numerical model was investigated by executing model runs with a range of polders constructed along the Sibsa river (LTMRA-18, 2020 – see Figure 3-16). Some of these polders are based on actual TRM operations (Pakimara and Bhania) whereas the others are fictious (but meant to provide an indication of the effect of large-scale TRM). The purpose of the experiment was to see to what extent simultaneous TRM along the Hari river (Beel Bhania and fictious polders) would influence siltation in Beel Bhania, but also in Beel Pakimara (along the Kobadak river).

TRM in Beel Pakimara and Bhania lead to beel-averaged siltation rates of 0.4 meter per year (Figure 3-17, which is in reasonable agreement with observation reported by Gain et al., 2017) and erosion of the Kobadak river (LTMRA-18, 2020). Adding additional TRM sites along the Hari has no substantial impact on deposition in Pakimara (Figure 3-17) or on erosion of the Kobadak river. However, deposition rates in Beel Bhania strongly decreased as more TRM sites were added (Figure 3-17). Upscaling of TRM therefore leads to lower sedimentation rates in the various flooded beels. However, the effect of TRM is two-fold: it aims not only to higher bed levels in the polders but also to erosion of the peripheral rivers. With more polders being flooded, the erosion rates in the peripheral rivers will also increase. Revitalising these peripheral rivers will also counteract the tidal amplification in the main river systems even though locally the tides in the peripheral will become larger as the channels are re-activated. The reduction in high waters and reduction of available sediment resulting from upscaling of TRM will lead to less frequent water logging problems. So even though the sedimentation rates in the beels decline as a result of upscaling TRM, upscaling still provides a potential solution for water logging in the polders. Unfortunately, the widening of peripheral rivers in response to upscaling of TRM may lead to another problem, related to bank erosion.

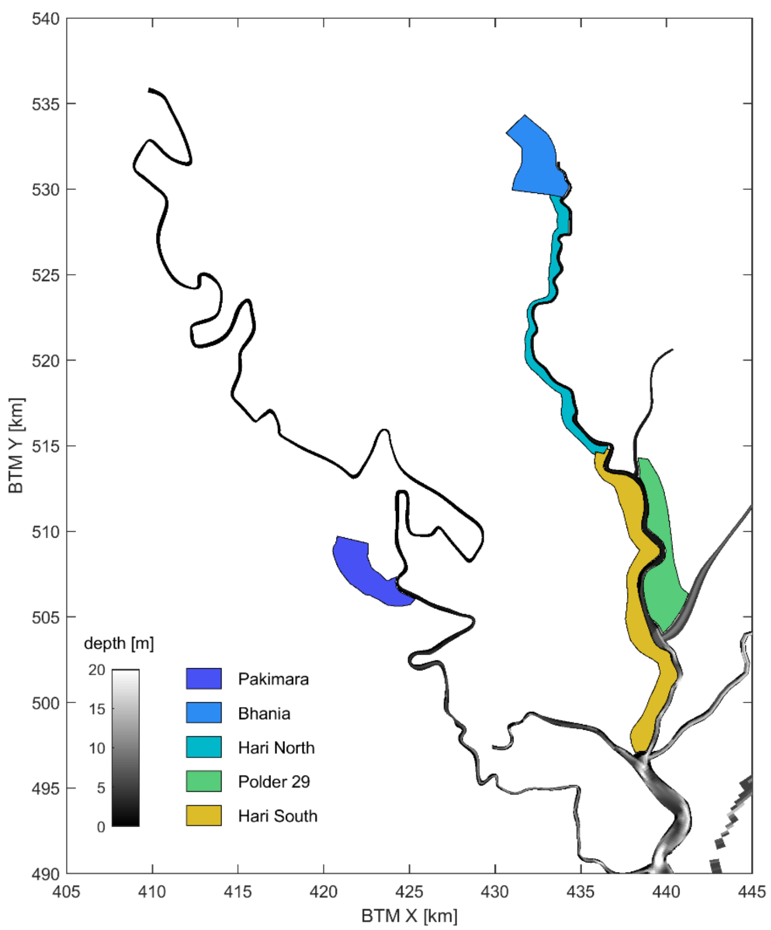

Figure 3-16 Definition of flooded intertidal areas used for upscaling of TRM. From LTMRA-18.

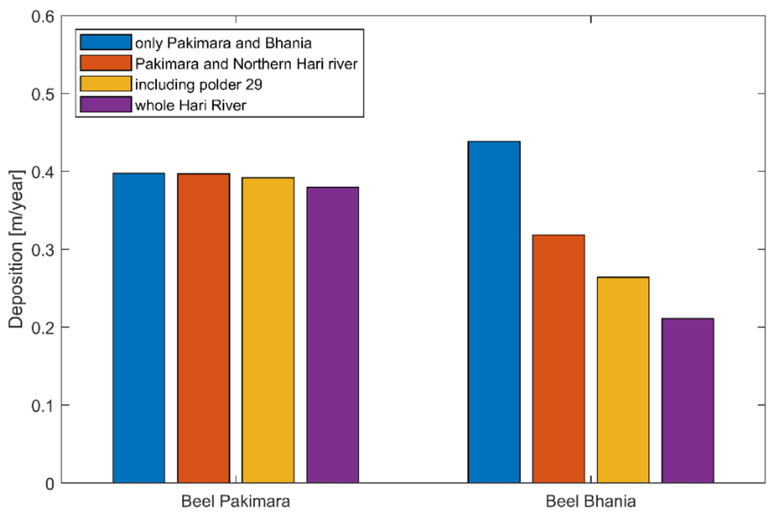

Figure 3-17 Deposition rates in Beel Pakimara and Beel Bhania, with only TRM executed in Pakimara and Bhania (blue), including the Northern Hari river (red), further including polder 29 (yellow), and Pakimara and the whole Hari floodplain as TRM location. From LTMRA-18.

At present there is no or only very limited bank erosion along the blind peripheral rivers. This will remain so as long as these rivers remain inactive. However, revitalizing the blind peripheral rivers through (upscaling of) TRM reintroduces tidal currents which may undermine the embankments of polders along these peripheral rivers. With higher present-day tidal amplitudes compared to pre-polder conditions, tidal velocities may also become larger than for pre-polder conditions. This aspect should be critically considered when considering TRM (upscaling).

Upscaling of TRM also leads to lower water levels and slower tidal propagation. Small-scale TRM deployment typically leads to higher tidal amplitudes because the river is eroded and the tidal volume through the channel increases (LTMRA-64). However, When TRM is simultaneously applied over a larger area, then the tidal storage effect becomes important as well. The volume of the incoming tidal wave spreads over the intertidal areas and inundated polders, leading to a landward reduction of the amplitude of the incoming tidal wave. This is essentially the opposite of the changes in tidal dynamics in the past 60 years in the Passur-Sibsa system and exemplified with the numerical TRM experiments in Figure 3-18. Large-scale reduction of the tidal amplitudes in the Sibsa estuary would reduce flow from the Sibsa estuary to the Passur estuary through the connecting rivers. This implies that TRM upscaling in the Sibsa estuary could mitigate bank erosion along the connecting rivers and at the same time reduce the large siltation rates in the Passur estuary near Mongla.

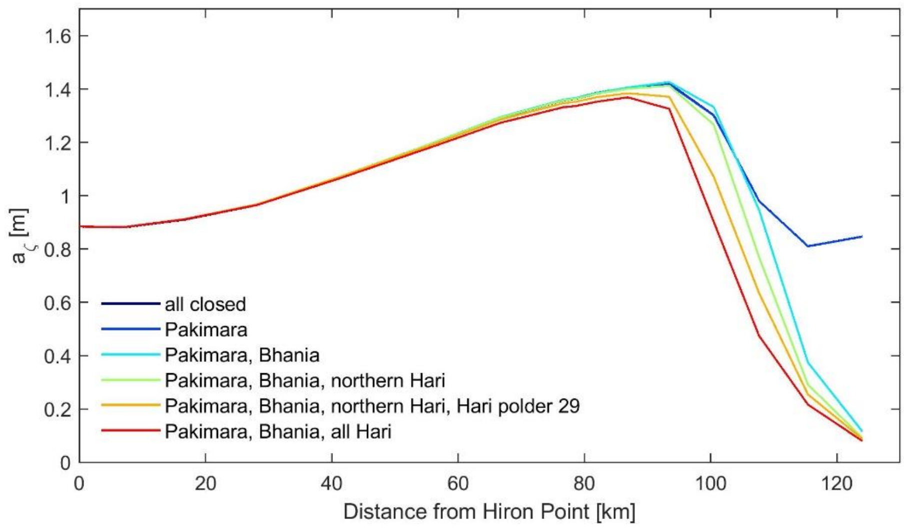

Figure 3-18 Modelled amplitude of the M2 tide along the thalweg of the Sibsa / Hari River for several polder configurations where progressively more polders are numerically included (see Figure 3-16 for locations of the polders). Beel Pakimara has no effect on tidal dynamics in the Hari river, the lines of 'all closed' and 'Pakimara' overlap. From LTMRA-18.

3.2.4 Micro-scale interventions: tidal river management

Tidal river management aims to increase the bed level of inundated polders and scour the blind peripheral rivers connecting the polders to larger estuaries, in order to efficiently drain rainwater. Tidal river management has a physical component (how to most efficiently raise land and scour peripheral rivers) and a social component (involving stakeholder participation, financial gains and investment, relocation of people). The section hereafter focusses on the physical aspects of TRM.

An important physical aspect of Tidal River Management (TRM) is an even distribution of sediment deposition during TRM. Uneven distribution leads to poor drainage of the polders (as the outlets are blocked by sediment deposits and low-lying areas are only limitedly raised) which in turn leads to social unrest (with some farmers benefiting from TRM because their land is raised while others do not or even experience adverse effects). Even more, historic TRM cases revealed that siltation rates are higher in some TRM pilots compared to others, for reasons not known prior to TRM. There is therefore a need to (1) predict with sufficient accuracy what the sediment deposition rates during TRM will be, and (2) optimize the design of TRM to evenly distribute the sediment deposits and maximize siltation rates. Important aspects in this design phase are the use of existing drainage channels during such TRM experiments (Figure 3-19), but also to dredge channels in the polder prior to flooding in order to evenly distribute sediments throughout the polder.

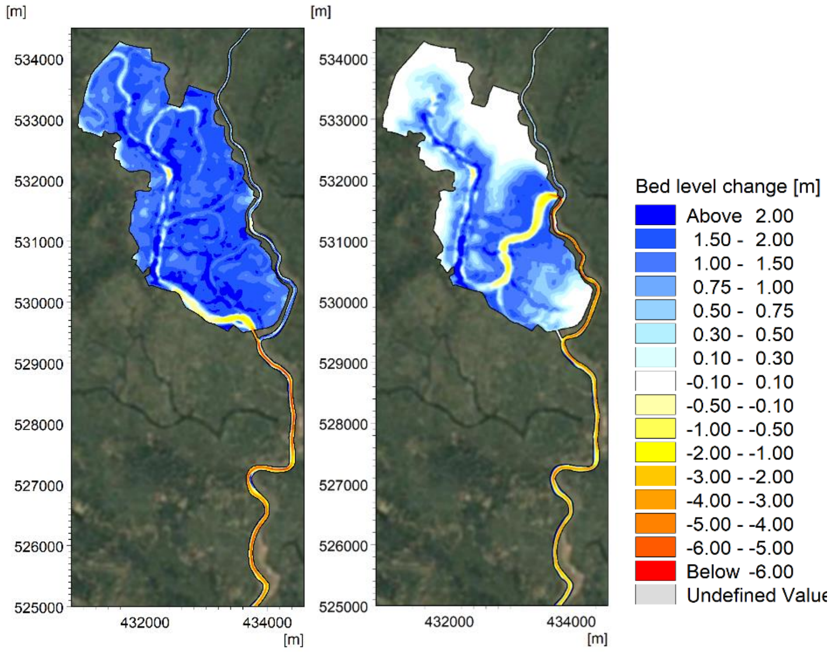

Figure 3-19 Bed level changes after 6 years in beel Bhania with opening in the South (left panel) and East (middle panel). From report LTMRA-64

The use of TRM to specifically mitigate accessibility problems for the port of Mongla has been tested with the MIKE-21 model for the Passur (LTMRA-69). For this purpose, TRM was numerically executed in polder 29 (opposite of the port of Mongla) – see Figure 3-20. These numerical experiments reveal that scouring will take place close to the intakes (resulting in 1-3 meter lowering of bed levels in a 5-year period) but also that siltation will take place just north and south of the eroding sections. These sedimentation zones are partly the result of the connection of the Passur river with the Sibsa river: additional tidal prism (which scours the area around Mongla) is partly drawn from the Sibsa river.

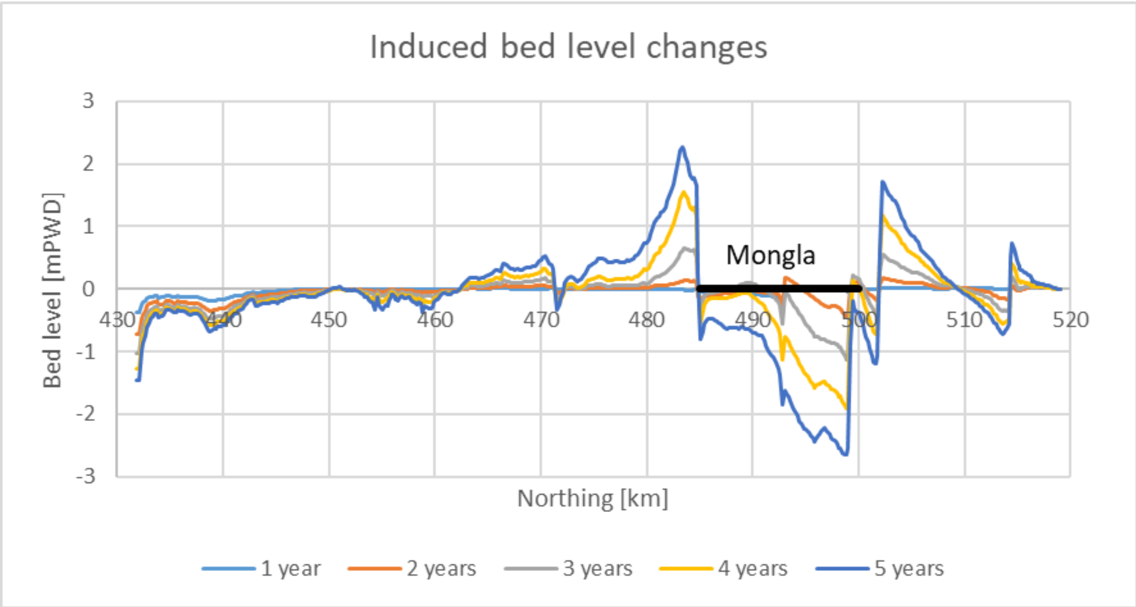

Figure 3-20 Simulated induced changes during the anticipated 5 years of operation. From LTMRA-69.

4 Impact of future developments on polders

In Chapter 3 we evaluated how climate change and anthropogenic effects may impact the dynamics of the delta on various levels. In this chapter we synthesize these impacts in a coherent way to establish their combined impact on the polders (section 4.1) and measures to mitigate negative impacts (section 4.2).

4.1 Future scenarios

4.1.1 Flood risk

Flood risk will increase due to a combination of sea level rise, subsidence, changes in tidal dynamics, and increasing cyclonic wind speeds. For these changes it is important to distinguish between polders located in the main estuaries and those close to the Bay of Bengal. Water levels along polders close to the Bay of Bengal are influenced by the tidal dynamics in the Bay of Bengal only, and not by internal dynamics in the various distributaries. In these areas, the largest contribution to flood risk changes is subsidence (up to 2050) and sea level rise (after 2050, when rates of sea level rise are expected to outpace subsidence rates). Subsidence rates are in the order of 5 mm/yr (40 cm by 2100), whereas sea level rise may be one meter higher by 2100 (extreme 5% RCP8.5 scenario). The impact of storm surges increases from west to east (with highest storm surges occurring in the Northeast of the Bay of Bengal). A projected increase in cyclonic speeds may lead to an increase of ~60 cm in storm surge height for 1:100 year recurrence conditions. Heightening of the embankments will be required for maintaining the safety against flooding.

In the landward direction, changes in tidal dynamics become increasingly important. At the mouth of the various distributaries, modified tidal dynamics in the Bay of Bengal will add approximately 10 cm to high water levels. However, in the landward direction the tidal dynamics are increasingly influenced by human interventions. In the Passur and Sibsa rivers, human interventions (mainly the construction of polders) have led to strong tidal amplification (up to a 2 meter increase in the tidal range between 1960 and 2020). The resulting increase of high waters has been over 1 meter. But importantly, the tidal range is still increasing because the system is still (after 60 years) adapting to the construction of polders. It is unknown how long this tidal amplification increase will continue, but it is likely that it will continue for at least the coming decade. The required future heightening of the embankments for maintaining the safety against flooding needs to be determined per polder.

4.1.2 Embankment failure

Bank erosion leads to land loss and in some cases can even endanger the stability of embankments protecting the polders. It is predicted that in the coming decades the locations of bank erosion as well as the corresponding erosion rate will remain to a large extent the same as presently observed (LTMRA-67, LTMRA-68, LTMRA-69, and LTMRA-70) - erosion may result from natural lateral channel migration, but also from local channel network reorganization or tidal amplification (both often as a result of human interventions). The impact of climate change on bank erosion is negligible compared to the large observed rates. Every bank erosion is to a certain point unique and needs to be individually analysed for underlying mechanisms and consequently mitigating measures. Some of these measures may be local (construction of groynes, smart dredging and disposal) or large-scale (influencing the tidal channel network).

4.1.3 Reclamation opportunities

Several areas in the mouth and east of the Meghna estuary rapidly accrete. Polders developed landward of such accreting areas will not suffer from erosion for a long period of time. However, freshly accreting shoals have a natural tendency to episodically revert to erosion. Although absolute accretion rates may be limitedly affected by sea level rise, the relative accumulation rates slow down because of rising water levels. Modelling results suggest that after 2050 the natural sedimentation rates are insufficient to keep pace with sea level rise, even in the rapidly accreting sections of the Meghna estuary (Figure 3-7, third panel). This may be partly compensated, however, by an increase in river discharge and sediment load resulting from the projected larger precipitation rates. Unfortunately, most of the increase in sediment load expected as a result from climate change will be at least partly compensated by human interventions in the upstream river basins, rendering a decline in the sediment load more likely. As a consequence, the opportunities to develop new agricultural land will progressively decline in the future and may almost completely disappear by 2050.

4.1.4 Polder drainage

Polder drainage is influenced by (1) water level differences inside the polders and outside the polders, (2) drainage capacity within the polders (resulting from shoaling but also local constructions), and (3) congestion of the sluices and channel siltation.

Water level difference

The drainage of polders will become increasingly more difficult because of sea level rise and subsidence (and further landward also by tidal amplification). In most polders the original ground level of the polders was close to the highwater level, allowing drainage throughout the tidal cycle. At present, the ground level has lowered to values around mean sea level, still allowing drainage during half of the tidal cycle. However, with the expected rates of subsidence (5 mm/yr, or 15 cm in 2050 and 40 cm in 2100) and upper bound of the RCP8.5 scenario for sea level rise (47 in 2050 and 105 cm in 2100) drainage by gravitational flow will become impossible for many polders between 2050 and 2100.

Drainage within polders

The drainage capacity within the polders depends on local maintenance and governance. Larger-scale human interventions or climate change have little impact on drainage capacity inside the polders (other than the water level difference and congestion of the sluices).

Congestion of the sluices and channel siltation

Infilling of channels surrounding the polders have negative influence on the drainage. This infill of the blind peripheral rivers is the result of lower flow velocities (in response of a reduction in tidal prism) and large availability of sediment. It is likely that the present-day infill of these peripheral rivers will continue and consequently drainage congestion problems will worsen, unless TRM is applied at a larger scale.

4.1.5 Freshwater supply

Climate change introduces mechanisms that may either increase or decrease the salinity. The total discharge and rainfall rates are expected to increase under climate change, leading to a reduction in salinity. However, there are also mechanisms promoting an increase in salinity:

- Precipitation is expected to increase in the wet season, but to decrease in the dry season. Since high salinity values are especially an issue in the dry season, freshwater shortages will increase with the expected climate-change induced weather patterns.
- Sea level rise will lead to more salt intrusion because the channels become relatively deeper.

- Human interventions in the upstream basin will probably lead to a further imbalance between water flow in the dry and wet season, by only limitedly influencing the flow in the wet season while reducing the flow in the dry season.
- The tides are still amplifying in response to historic human interventions. Large tidal amplitudes typically lead to more salt intrusion. Therefore, the salinity will continue to increase in the coming decades, independent of climate factors or new human interventions.

Overall, salt intrusion will therefore become progressively more sever leading to fresh water supply problems. Especially the middle and embanked part of the delta will be impacted by SLR, causing serious freshwater shortage for the polders in this area in the dry season, due to significant landwards movement of the 1 ppt (drinking water limit) and 2 ppt salinity (irrigation water limit) line (Figure 3-9, LTMRA-63).

4.2 Mitigating measures

4.2.1 Tidal river management

The southwest Ganges-Brahmaputra delta changed from an extensive mangrove-fringed tidal creek network (Figure 4-1a) into an embanked system with limited tidal storage (Figure 4-1b). This has led to sinking of polders, infilling of peripheral rivers (both leading to water logging) and amplification of the tides (which in turn generates bank erosion problems). One way to mitigate these issues is Tidal River Management (TRM). Up to now TRM is executed locally to improve drainage conditions of polders, which is primarily a short-term and small-scale gain. However, on the long term, TRM also provides a way to grow with sea level rise and reduce tidal amplifications (compared to their present amplitude or at least relative to the autonomous development, which is continuous amplification). Both growing with sea level rise and large-scale tidal management could provide an additional motivation for implementing TRM, but then executed at a large spatial scale (Figure 4-1c).

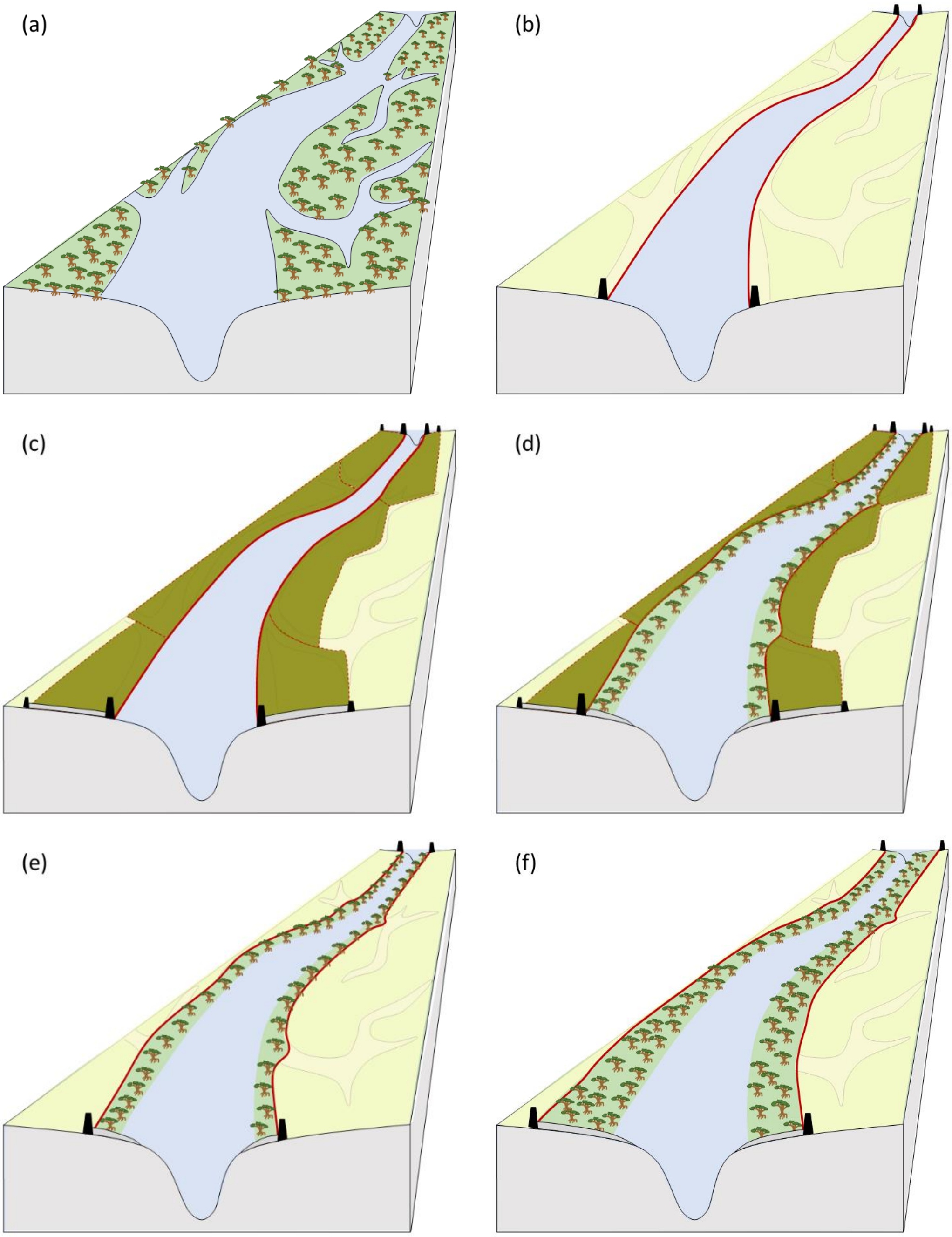

Figure 4-1 Illustration of large-scale mitigating measures aiming at sustainable polder development by modifying tidal dynamics and promoting sedimentation. Panel (a) is the natural situation predating human settlement, provided as a reference, with extensive mangrove-fringed creeks and intertidal areas. Panel (b) is the present situation, with solid embankments protecting reclaimed areas. Measure (c) is large-scale TRM along the estuary banks, generating an area which grows with sea level rise but also dissipates the tidal wave. Measure (d) is a combination of measure (c) and managed realignment (providing space for mangroves to develop). Measure (e) is limited managed realignment, in which the estuary is widened several 10%; measure (f) is similar but with a doubling of the intertidal area. Both interventions aim at dissipating tidal energy (i.e. reducing the tidal amplitude or limiting its ongoing amplification); the wider the channel the more effective the tide is dissipated. The new soft embankments will be naturally grown with mangroves, which allow the riverbanks to grow with sea level rise by trapping of sediments.

When evaluating TRM over short timescales (years – decades) the adverse effects (temporal loss of agricultural land and related social issues) may be larger than the benefits (improved drainage and therefore more agricultural output). But over longer timescales (the year 2100 or 2200) the benefits of TRM become more prominent. Without TRM, the ground-level of many of the current polders will be well below mean sea level because of accelerated Sea Level Rise and subsidence (around 1 meter by 2100, over 3 meters by 2200). Because of the vulnerability of the delta (cyclones, river floods) in combination with the loose subsoil (complicating construction of solid embankments) flood risks will increase strongly in time. The abundancy of sediments, however, may provide a means for the delta to partially grow with sea level rise through structural implementation of TRM. This could be in the form of a rotating TRM scheme where all low-lying land is inundated for 2-3 years every 30 – 50 years. This would allow the polders to maintain their drainage capacity, but on the long term more importantly: keep pace with Sea Level Rise.

For upscaling TRM sediment availability may become a limiting factor (see section 3.2.3). This requires careful planning and studying upscaling of TRM, but also a timely start.

4.2.2 Dredging and disposal of sediment

Dredging of the riverbed is necessary to maintain access for shipping in areas suffering from shoaling. A number of dredging strategies can be devised that either use maintenance dredging (that was to be executed anyway) in a way it has additional benefits, or to deploy capital dredging in a way it may improve the functioning of the system.

An example of smart maintenance dredging and disposal is to release sediment dredged from the Passur river (for providing access to the port of Mongla) in nearby connecting rivers in order to reduce the tidal discharge through these channels. This placement may reduce the tidal discharge conveyed by these channels, or at least slow down the progressive increase. Placement of this dredged sediment should be carefully planned: disposal in the middle of the channel may strengthening lateral expansion of the channel and thereby lead to more bank erosion. Sediment should preferably be place close to eroding shores in a location with a relatively stable opposite riverbank.

This dredging strategy may be upscaled with capital dredging, aiming at restoring the tidal dynamics in the Passur-Sibsa estuary. The Passur river is silting up because tides propagate from the Sibsa river to the Passur river; this in turn is the result of the larger water depth in the Sibsa river leading to faster tidal propagation. There are two ways to increase the speed of the tidal wave travelling through the Passur river faster relative to the Sibsa river. One is to restore more intertidal area in the Sibsa river (see sections 4.2.1 and 4.2.4); the other is to deepen the Passur river. When the Passur river is sufficiently deep, the tidal propagation speed may become sufficiently large to prevent flow from the Sibsa to the Passur through the connecting channels. This will then also reduce the rapid shoaling in the Passur river, and bank erosion in the connecting channels. In order to monitor the success of such measures it is necessary to have a well-functioning observational and modelling programme in place, to compare the observed changes with a situation without any mitigating measures.

Dredging may also be used to reduce bank erosion in the larger channels. In some channels (Baleswar, Meghna estuaries) bank erosion is the result of deflection of tidal and river flow by accreting channel or mouth bars. One way of alleviating bank erosion is therefore to dredge the channel bars and mouth bars, and dispose the sediment close to the eroding banks. Numerical experiments in the Baleshwar river suggest that dredging may be very effective in mitigating bank erosion, but smart placement of the dredged material is even more important (section 3.2.3). Such measures may also be undertaken in the Meghna Estuary. Channel bars that started appearing around the year 2000 (blue channel bars in Figure 4-2) which probably contributes substantially to the very large bank erosion rates (Figure 2-14). These bars are presently only marginally inhabited. Smart dredging of the upstream sections of these bars (at deeper water) would set in motion where these bars gradually disappear and migrate seaward. Their disappearance would already alleviate bank erosion rates, but disposing the dredged sediment close to the shorelines would have an even greater mitigating effect. Alternatively, the dredged sediment could be mined, rendering the option economically interesting.

Figure 4-2 Channel bars of which removal through dredging will alleviate bank erosion (in blue, the size of the channel bars).

4.2.3 Closure of channels

Closure of the channels between the polders and connecting the Passur and Sibsa rivers stop bank erosion along these connecting channels and probably the downstream Sibsa river, less shoaling in the Passur river, and a reduction of the tidal range in the upper Passur / Rupsha river. However, closure also has (likely negative) side effects which need to be carefully evaluated in advance. Based on expert judgement and interpretation of data and numerical model results, closure of the connecting channels will have the following side effects:

- The tides in the upper Sibsa rivers (Kobadak, Hari) will amplify. This may have positive impacts (scouring of the channels, better drainage) but will also lead to higher highwater levels.
- Similarly, the reduction of the tidal amplitude in the upper Passur / Rupsha river may also have negative side effects (poorer drainage, siltation of channels).
- The higher flow rates through the Passur may lead to bank erosion in its lower reaches.
- The salinity in the Sibsa river will increase.
- Closure of the channels will negatively impact shipping.
- The connecting channels will become blind (dead end) channels. Such blind channels will function as sediment sinks and their infilling may negatively influence the drainage of the adjacent polders.
- Erosion of the Sundarbans between Passur and Sibsa downstream of the polders or even generation of new connecting channels within the Sundarbans.

The connecting channels have been extensively studied in the Passur-Sibsa system, and their closure may have important positive impact. However, a lot more of such connecting channels exist throughout the Ganges-Brahmaputra delta, especially in the vicinity of the Sundarbans. Closure of such channels may also be considered for other connecting channels which suffer from bank erosion, especially if they are limitedly used for navigation purposes. However, closure of channels in complex, connected tidal networks is likely to set in motion a chain of events which may constitute negative impacts. Every hard intervention in such a channel network needs to be carefully investigated with appropriate numerical tools in combination with dedicated field observations.

4.2.4 Development of mangrove-fringed intertidal areas

Mangroves dissipate tidal energy and trap sediments. The most natural solution for many of the problems in the delta would be to convert reclaimed land into mangrove-fringed floodplains across a width of several 100’s of meter (Figure 4-1e) to (preferably) kilometres (Figure 4-1f). These mangrove fringes trap sediments and reduce the tidal amplitude and propagation speed. Under normal circumstances, a mangrove fringe of several 100’s meter wide would quickly fill up with sediments, losing its efficiency. However, as a result of sea level rise and subsidence, these areas can store much more sediment than they would otherwise be able to do. Additional advantages of mangrove fringes are

- They reduce the impact of storm surges on the embankments (Figure 4-3a, b). The required height or strength of embankments separated by a healthy mangrove forest is lower than for an embankment facing the open sea. Such benefits have not yet been quantitatively explored in Bangladesh.
- Bank erosion will not threaten embankments (Figure 4-3c, d). The mangrove forest episodically erodes or accretes, without eroding the embankments. In addition to the required height and strength of the embankments, this would also require a smaller apron (representing an important financial benefit).

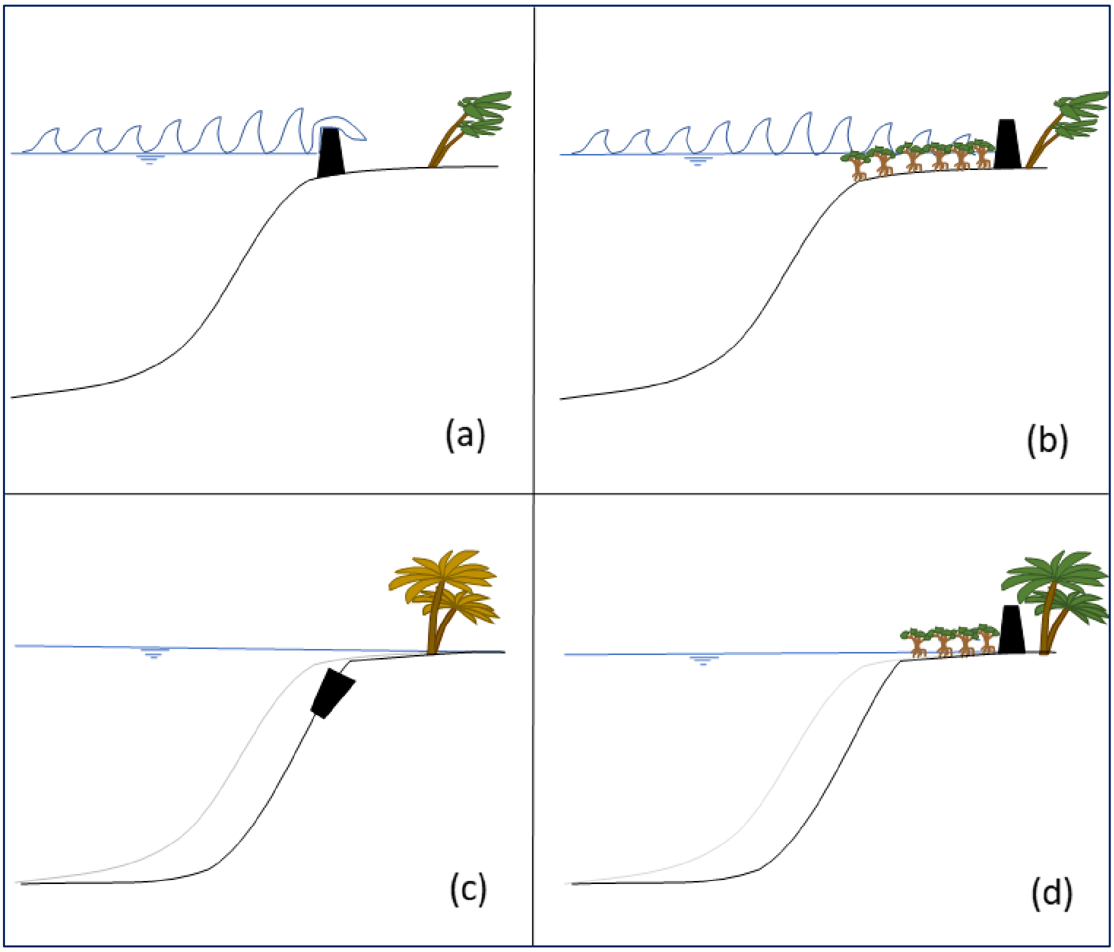

Figure 4-3 Advantage of a mangrove green belt in front of embankments. Mangroves dissipate wave energy reducing the wave height at the embankments during storm conditions (a, b). Mangroves also provide a protective barrier seaward of the embankment during erosion event. Without mangroves, erosion and undercutting of the embankment may lead to failure and immediate flooding. A wide mangrove belt may be eroded over a considerable width while still protecting the embankments (c, d). Mangroves are resilient: erosion during episodic high energy events may be compensated by sedimentation during more quiet conditions.

4.2.5 Integral, nature-based solutions

The distributaries of the Ganges-Brahmaputra delta provided a complex, coupled system where interventions in one part of the system may influence (both negatively and positively) other parts of the system. This is exemplified with the Passur-Sibsa system, where the creation of polders set in motion a number of processes that amplify tides and reorganize the channel network leading to abandonment of some channels and expansion of others. The preferential solution to manage these issues is to develop a holistic green-gray infrastructure approach, composed of some of the mitigating measures described above with an emphasis on nature-based solutions. Erosion of the banks of the connecting rivers may be mitigated by closing them (as in section 4.2.3), but a similar solution may be achieved by

1. Slowing down the propagation speed of the tidal wave in the Sibsa river. This may be achieved through large-scale TRM in the Sibsa river (section 3.2.3 and 4.2.1, for instance polders 18-22, 31 and 32) or converting some reclaimed land along the Sibsa river to mangrove swamps (section to 4.2.4)
2. Expanding the cross-sectional area of the Passur River by dredging (section 4.2.2). Without other simultaneous interventions the dredged volume would be rapidly deposited because of

governing hydrodynamics, but by simultaneously modifying the hydrodynamics in the Sibsa and the Passur river, dredging may be successful (see section 3.2.3).
3. Disposing the sediment in the connecting channels to reduce the propagation speed of the tides through these channels (see also section 3.2.3).

This set of measures will lead to (1) a reduction in bank erosion along the Sibsa river and connecting rivers, (2) reduce shoaling of the Passur river near Mongla, and (3) prevent further amplification (and maybe even reduction) of the tides.

4.2.6 Improvement of drainage infrastructure

With increasing relative sea level rise, the time window during which polders are able to drain excess rainwater by gravitational outflow will become progressively shorter. At a certain moment, drainage of rainwater will only be possible using (1) pump systems or (2) by raising the ground level of the polders and lowering the discharge capacity in the peripheral rivers. Raising of the bed levels and increasing the discharge capacity of peripheral rivers may be achieved through tidal river management. However, raising ground levels over a larger area requires upscaling of TRM, for which sediment availability may, in time, become a limiting factor.

Drainage issues in the polders are partly related to the offshore water levels relative to the ground level of the polder, but also by the flow capacity within the polders through the khals. Improving this drainage capacity of the khals (by deepening, cleaning, or removing structures) will reduce flooding of the polders during periods of rainfall.

5 Synthesis

5.1 Future development

The main conclusions concerning future development of the delta from the present study are the following:

(1) The highwater levels with respect to ground level, which is relevant for flood defence, will increase in absolute values and in frequency

- Highwater levels will increase in the future as a result of climate change (relative sea level rise, higher cyclonic wind velocities leading to higher storm surges), subsidence, and tidal amplification in response to sea level rise and human interventions (especially in the more landward parts of the delta).
- Subsidence is a continuing process, and its rate is only limitedly influenced by human interventions. The impact of climate change depends strongly on the climate change scenario.
- Rising highwaters in the seaward polders are most strongly influenced by subsidence on the short term (up to 2050) and by sea level rise on the longer term (2100, although depending on the climate change scenario this may also be sooner).
- Highwaters in the more landward polders in the southwest delta (north of the Sundarbans) are additionally influenced by tidal amplification in response to human interventions. Tidal amplification has the biggest impact on highwater levels (but not on mean sea levels, which is only influenced by subsidence and sea level rise).

(2) The river discharge and sediment load will change due to climate change and human interventions

- Climate change will lead to higher river discharges and sediment loads in the wet season (because of higher precipitation rates and prognoses on deforestation and agriculture development in the upstream catchment)
- Human interventions in the upstream catchment and climate change will probably lead to a reduction of river discharge in the dry season.
- Construction of reservoirs and diversion of water flows in the upstream catchment will probably lead to a reduction in the sediment load.
- It is not known which impact is larger on the sediment load (increase by climate change or decrease by human interventions)

(3) The salinity of surface waters in the southwest delta will increase, if no measure is taken to increase the flow diversion via the Gorai river.

- The precipitation and river discharge will reduce in the dry season (leading to more saline conditions in the period). Salt intrusion is an issue.
- Sea level rise will lead to more saline conditions, especially in the middle and embanked part of the delta.
- Continues tidal amplification will probably also lead to more salt intrusion.
- The projected increase in salinity may only be mitigated by reconnecting relict river branches with the Ganges, or by conveying more freshwater flow through existing branches such as the Gorai river.

(4) The southeast of the delta will continue to expand seawards for most climate change scenarios, but the southwest delta will suffer from shoreline erosion due to a decline in sediment availability

- The Meghna estuary will continue to grow until 2100 with a limited sea level rise and the expected increase in the sediment load of the Ganges and Brahmaputra in response to climate change.
- Even with such an increasing sediment load, the Meghna estuary will revert to a land loss after 2050 for a high rate of sea level rise (5% upper limit of RCP 8.5).
- The southwest delta may become sediment-starved and erode.

(5) In some areas bank erosion results from natural channel dynamics, but in some areas bank erosion is also cause by human interventions

- Some channels suffer from bank erosion as a natural process (lateral migration of channels). When designing embankments, this natural tendency should be accounted for by strategic (landward) placement of embankments, bank protection, or smart dredging.
- Other channels erode as a response to human interventions leading to widening of channels. These cases may be mitigated by e.g. closing the channels.

(6) Present-day poor polder drainage is the combined result of poor maintenance of the hydraulic infrastructure, relative sea level rise (subsidence and sea level rise), and infilling of the peripheral rivers; this will become worse under projected climate change

- The change in relative sea level rise (subsidence and absolute sea level rise) has not progressed enough to completely explain poor drainage conditions. With progressive subsidence and accelerated sea level rise gravitational drainage in many polders will become progressively less effective in time.
- Poor drainage is also the result of lack of maintenance of the hydraulic infrastructure (khals and regulators) because of local adaptations to these infrastructural works and because of large siltation rates.
- In the landward polders the infilling of tidal rivers with sediment is an additional important issue, which is a response of the impact of polder construction on tidal flows.

5.2 Identified knowledge gaps

The key knowledge gaps in our understanding of the functioning of the delta are the following

- What is the upstream sediment load (see also section 2.1)? How will this change to human interventions?
- What is the sediment supply from the Meghna to the southwest delta through the Bay of Bengal (see also section 2.1)? What is the role of waves and wind-driven flows herein?
- What is the historical development of the southwest delta other than the Passur-Sibsa system? How have channels developed and how much have the tides amplified?
- For how long will tidal amplification in the delta continue, and up to what range? How will these tidal highwaters influence peak highwaters?
- What are present-day infill rates in the peripheral channels and how does this influence the sediment budget and tidal dynamics?
- What is the role of cyclones in shaping the delta (coastline erosion, deposition in the Sundarbans)?
- How will the Sundarbans respond to climate change (rapid drowning by increasing sea level rise and/or sediment shortage, change in salinity) and human interventions? How would a possible degradation of the Sundarbans influence the polders in the southwest delta?

6 Recommendations

6.1 Interventions

The Ganges-Brahmaputra delta is a complicated system because of its large size, the large sediment load, the large amount of concurrent human interventions in the delta but also the upstream catchment, and climate change and sea level rise. All interventions therefore need to be based on system knowledge and carefully planned and studied, in order to (1) account for indirect effects of any intervention, and (2) strengthen (or weaken) natural tendencies in the system. Their economic costs and benefits as well as social and environmental impact may then be evaluated in a later stage. The following interventions following this strategy are recommended on a system level:

(1) Develop a Sediment Management Strategy

- The sediment load of the Ganges and the Brahmaputra strongly influence the loss and the development of land in the delta. A system-wide sediment strategy should be developed, implementing regulations that any intervention in the upstream catchment should account for the downstream impact. Such a sediment management strategy is necessary for sustainable delta development from a physical point of view, but probably requires cross-ministerial cooperation (including BWDB, BIWTA, and other ministries and agencies).
- Continuously monitor the state of the delta by (1) developing a monitoring strategy, (2) a system to continuously analyse these data (including through the use of models), and (3) an institutional framework to develop the programme and apply its results. This program should include tidal dynamics, sediment concentrations, and salinity and is an overarching requirement in order to quantify the impact of interventions listed below.

(2) Restore the tidal dynamics in the delta distributaries in order to lower high waters and reduce bank erosion rates. This can be done in two ways:

- Close the connecting channels. Closing the connecting channels in the Passur-Sibsa system will immediately lead to a reduction of bank erosion rates in the downstream Sibsa river and the connecting rivers, and will reduce shoaling of the Passur river. However, it also has a number of other effects related to tidal amplification and damping in other areas, freshwater availability, and accessibility.
- Develop an integral, system-based approach combining a number of soft interventions (in addition to hard interventions such as improved embankments) to improve tidal dynamics. These would include (1) development of intertidal storage in the Sibsa river (by either TRM or by restoration of mangrove fringes) and (2) significantly deepening the Passur river and disposing the dredged sediment in the connecting channels.

(3) Re-introduce flows from the Ganges river to the Bay of Bengal through the Gorai and other (smaller) distributaries in order to

- Reduce the salinity in the various distributaries (notably in the southwest delta). On the long term, a sufficient amount of freshwater is necessary to provide local households from surface water (rather than using groundwater which leads to subsidence and may be polluted).
- Re-vitalize the smaller rivers, which is beneficial for polder drainage and navigation purposes. This will lead to better navigability and reduce tidal amplification in the major estuaries.

(4) Restoration of mangrove fringes, for three reasons

- Developing a delta that partly grows with sea level rise, creating a more climate resilient delta.
- Strengthening coastal defences (or allowing for smaller coastal defences) by dissipating wave energy and by providing a buffer protecting the embankments during erosive events.
- Reduce tidal amplification, thereby reducing bank erosion rates and lowering high water levels

Recommendations on a micro-scale (polder) level are strongly site-specific and can therefore only limitedly be generalised. Nevertheless, the following interventions are recommended to execute on the scale of polders and local rivers:

(1) Smart dredging and disposal

- Mitigate bank erosion by removing middle and mouth bars in areas where sideways deflection leads to bank erosion. Deposit the dredged sediment in the channels (which may be as important or even more important than the removal of sediment).
- Dispose sediment dredged as part of maintenance dredging works in areas where they have beneficial effects (near eroding riverbanks or in the channels connecting the Passur and Sibsa rivers).

(2) Execute tidal river management in low-lying areas suffering from poor drainage. When executing TRM the following aspects should be considered:

- TRM should be well designed in order to evenly distribute the sediment deposits.
- Upscaling of TRM may lead to local sediment shortage when TRM is executed in polders close to each other. It is recommended to develop a TRM cycle in which simultaneous TRM operations are executed in different river systems.
- TRM is, together with mangrove development, the most sustainable way to develop a climate-proof delta. When considering TRM applications, this long-term prospect should be made clear.
- Address socio-economic issues sufficiently – these aspects are more complex than physical feasibility. Also consider renaming TRM, which has acquired a negative connotation.

(3) Maintain the regulators and khals. Many of the drainage issues are not the result of sea level rise or subsidence, but poor maintenance. This covers two aspects:

- Dredging of the khals and the area seaward of the regulator. Many khals and regulators / sluices have become useless due to excessive siltation.
- Develop strategies to minimise misuse of the drainage systems by local inhabitants. When khals are partly blocked by local farmers to ensure water availability, then (1) jointly develop alternative ways the farmers can achieve their water demands and (2) explain more clearly what the impact of partial closures is on the long term.

6.2 Monitoring and modelling

Some of the knowledge gaps are the result of lack of continuous observations (monitoring) coupled with continuously improved models. The following recommendations are made in terms of monitoring:

- Constant monitoring the sediment load of the Ganges and Brahmaputra
- Regular monitoring of the sediment flux between the distributaries west of the Meghna estuaries and the Bay of Bengal.
- Set-up of a detailed monitoring campaign simultaneously measuring the water flux through all the connecting rivers (for system understanding and model calibration).
- Continue monitoring subsidence.
- Further develop models to analyse the present state of the delta, the expected impact of future interventions, and the impact of executed interventions.

6.3 Future activities

We propose to undertake the following activities aiming at better understanding of the impact of mitigating measures:

- Develop a nature-based integral solution (section 4.2.5) and quantify this with a model specifically setup for that purpose. The models developed as part of this project are multi-purpose, but addressing specific questions develops from the development of specific models. For instance, the development or adaptation of a meso-scale distributary model (such as the Passur-Sibsa) in which all peripheral rivers and connecting rivers are implemented in greater detail than in the existing models, including better observations of bed levels in the connecting rivers and polders or mangrove areas to be inundated. With such a model the impact of closure of individual channels, opening of polders, and deepening of the Passur river on tidal dynamics and sediment dynamics can be analysed systematically.
- Execute and closely monitor an actual pilot on removing a mid-channel or mouth bar (section 4.2.2), and compare this with numerical predictions on bank erosion rates.
- Extend models developed as part of this project by converting polder area to open water, and convert these polder areas to mangrove forests (section 4.2.4), in order to quantify their impact on tidal dynamics, bank erosion and storm surge conditions.
- Extend morphological models developed as part of this project with extreme conditions (especially typhoons) to quantify their impact on long-term morphology.

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