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)

30 Year impact of SLR and human interventions on the morphodynamics of meso-scale estuaries along the Bangladesh coast

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June 2022

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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

BTM- Bangladesh Transverse Mercator

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

PWD- Public Works Datum

RCP- Representative Concentration Pathways

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

Earlier studies describe the hydrodynamic and morphodynamic model calibration and validation of 4 meso-scale case studies along the Bangladesh coast (DHI and Deltares, 2020b,c,d,e). The 4 case studies are indicated in Figure 1 and comprise the Pussur-Sibsa system, the Baleswar-Bishkhali system, the Lower Meghna-Tetulia River system and the Sangu River system.

Based on the validated models, this report describes the modelled morphodynamic development of the 4 case studies as the result of 30 years of sea level rise and anthropogenic interventions. The latter includes dredging operations and the construction of cross-dams in support of land reclamation and shoreline protection. Boundary conditions for the scenario runs are derived from the macroscale model described in DHI and Deltares (2020a).

Comparison of scenarios provides insight into the impact of SLR and human interventions on the morphodynamic and hydrodynamic state of the estuaries ~30 years from present.

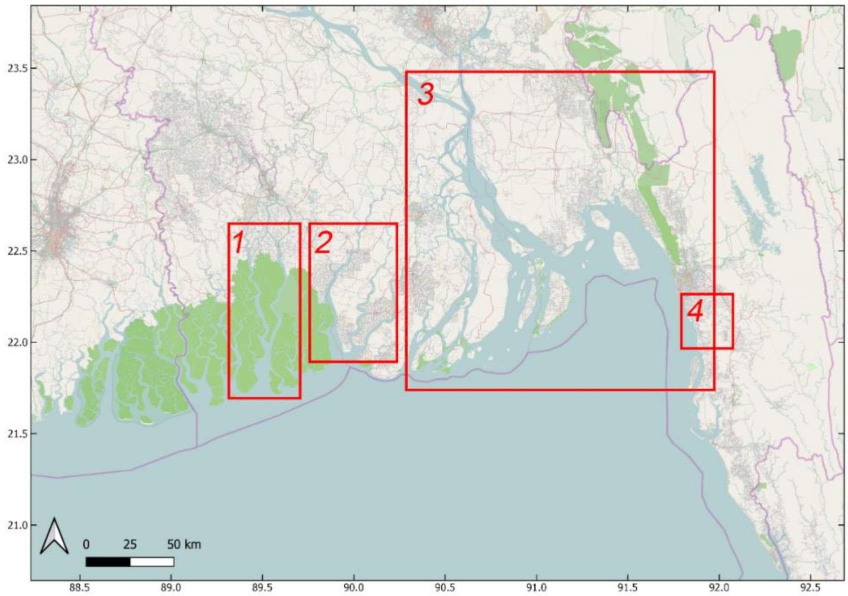

Figure 1 Map of meso-scale modelling domains for long-term morphology in the Bangladesh coastal zone: (1) Pussur-Sibsa; (2) Baleswar-Bishkhali; (3) Lower Meghna-Tetulia; (4) Sangu river

2 Summary of meso-scale models

The 4 meso-scale 2D models have been calibrated and validated against available data of water levels, discharges, suspended sediment concentrations at available stations. To derive river and tidal boundary conditions for the meso-scale models use was made of the macro-scale model (DHI and Deltares 2020a). Morphodynamic validation took place for periods that bathymetric surveys of the entire system were available, that is, between 2011-2019 (Pussur-Sibsa), 2011/2009-2019 (Baleswar-Bishkali), 2000-2009 (Lower Meghna), 2005-2018 (Sangu). Model results show that erosion and deposition volumes could be skilfully reproduced within acceptable range, despite the lack of observation data to feed the model (eg. on water levels and flow at the boundaries, sediment properties and bed composition) and given the use of rough schematizations and limited process descriptions that had to be applied due to data scarcity and to limit model runtime (DHI and Deltares, 2020b,c,d,e).

3 Objectives

The objectives of the current study are twofold:

- To explore the effects of macro-scale SLR and change in river discharge or sediment supply on meso-scale morphodynamic development across a variety of estuaries along the Bangladesh coast.
- To explore the impact of human interventions like access channel dredging operation and cross-dam construction relative to the impact of SLR.

4 Methodology

The four meso-scale models are forced by a discharge at the upstream boundaries and tidal conditions at downstream boundaries. There are no observed data available at these boundaries of the meso-scale models. Also, hydrodynamic data and SSC to describe the boundary conditions under scenarios of SLR are not readily deducible. Instead, we used the macro-scale model (DHI and Deltares 2020a) to derive historic and future (SLR scenarios) boundary conditions for the meso-scale models. Thus, the boundary conditions do not only include the rise in sea level at the seaward boundary, but also its effect on tidal propagation and the effect of bathymetric development throughout the entire macro-scale system including its (modelled) morphodynamic developments.

Though at the macro-scale, simulations were carried out over 2020-2100 without a significant deterioration of the model and producing realistic trends on an aggregated scale, simulating developments at the finer meso scale over periods longer than 30 years was not deemed useful, as the uncertainties in the evolution would likely be greater than the trends. Therefore, all meso-scale model simulations were limited to the period 2020-2050, which in itself was already a significant effort.

4.1 Macro-scale model scenarios setup

The macro-scale model was hydrodynamically calibrated against tidal conditions and discharges at various locations in the model domain. For decadal time-scale model hindcasts and future predictions the macro-scale model was forced by schematized boundary conditions (discharge, concentrations, wind) and was calibrated against sediment concentration patterns and observed volumetric changes in the model domain and coastal zone (DHI and Deltares 2020a). The different scenarios of the macro-scale model include current conditions, 0.5m SLR by 2100, 1m SLR by 2100, 50% sediment reduction (following observed trends) and decreased discharge (due to foreseen upstream damming). All scenarios included subsidence. The SLR in all scenarios followed a parabolic increase, as described in the macro-scale report (DHI and Deltares 2020a). The same scenarios were applied to the meso-scale models. Table-1 presents the list of these scenarios.

Table 1 Climate Change Scenarios

ID	Model	SLR	Discharge	SSC	Purpose	Simulation Period	Macro Model Boundary ID
PSC1	**Pussur-Sibsa**	0.0	$HYD_{RCP4.5}$	present value	no SLR	2020-2050	r043
PSC2		1.0	$HYD_{RCP4.5}$	present value	high-end SLR (standard scenario)	2020-2050	r042
BBC1	**Baleswar-Bishkhali**	0.0	$HYD_{RCP4.5}$	present value	no SLR	2020-2050	r043
BBC2		1.0	$HYD_{RCP4.5}$	present value	high-end SLR (standard scenario)	2020-2050	r042
MEC1	**Meghna Estuary**	0.0	$HYD_{RCP4.5}$	present value	no SLR	2020-2050	r043
MEC2		1.0	$HYD_{RCP4.5}$	present value	high-end SLR (standard scenario)	2020-2050	r042
MEC3		0.5	$HYD_{RCP4.5}$	present value	decreased discharge due to damming	2020-2050	r044
MEC4		0.5	$HYD_{RCP4.5}$, anthro. decrease	50% present value	Influence reduction sediment delivery, decreased discharge due to damming	2020-2050	r048
SC1	**Sangu**	0.0	$HYD_{RCP4.5}$	present value	no SLR	2020-2050	r043
SC2		1.0	$HYD_{RCP4.5}$	present value	high-end SLR (standard scenario)	2020-2050	r042

4.2 Meso-scale interventions

With respect to earlier studies (DHI and Deltares, 2020b,c,d,e), the meso-scale models were updated by including large-scale bank erosion, through the ‘dry cell erosion’ concept, where vertical erosion due to migrating channels is converted to erosion of adjacent dry cells. This is particularly important for maintaining realistic channel and shoal geometry through long morphodynamic simulations. Some meso-scale models were additionally optimised.

- Pussur-Sibsa Model - Inclusion of the side channels in the Pussur-Sibsa river system to better approximate the actual conditions;
- Meghna Estuary Model - Inclusion of existing bank protection works in Noakhali, Bhola and Manpura islands;
- Sangu Model - Inclusion of existing Embankment in Anwara and Bashkhali region.

Apart from the scenarios imposed by the macro-scale model defined in Table 1, several meso-scale area specific scenarios with human interventions were defined. These include the effects of cross-dam construction and dredging in the Lower Meghna Estuary Model and dredging in the Pussur-Sibsa

Model. The cross-dam construction in the Lower Meghna estuary is foreseen to promote land reclamation while dredging aims to reduce bank erosion in Meghna Estuary through thalweg shifting and to support navigability in the Pussur river. The duration of the runs exploring dredging impact was set at 10 years as this represents a realistic period for capital dredging and subsequent maintenance dredging. The list of the intervention scenarios is given in the following Table-2. Table 3 shows how the effects of different measures are assessed by subtracting different scenarios.

Table 2 Intervention Scenarios

ID	Model	Intervention	SLR	Discharge	SSC	Subsidence	Simulation Period	Macro Model Boundary ID
PSI1	**Pussur-Sibsa**	Dredging	0.0	$HYD_{RCP4.5}$	present value	yes	2020-2030	r043
MEI1	**Meghna Estuary**	Dredging	0.0	$HYD_{RCP4.5}$	present value	yes	2020-2030	r043
MEI3		Crossdam	0.5	$HYD_{RCP4.5}$	present value	yes	2020-2050	r043
MEI4		Crossdam	0.5	$HYD_{RCP4.5}$, anthro. decrease	present value	yes	2020-2050	r048

Table 3 Runs used to assess process effects 2D model simulations

Scenario	ID difference	Meso Models
Effect SSC reduction & Damming	C4-C3	Meghna Estuary
Effect 1m SLR	C2-C1	Pussur-Sibsa, Baleswar-Bishkhali, Meghna Estuary & Sangu
Effect of Dredging	I1-C1	Pussur-Sibsa, Meghna Estuary
Effect of Cross-dam	I3-C1	Meghna Estuary
Effect of Cross-dam under Moderate SLR & SSC reduction	I4-C4	Meghna Estuary

4.2.1 Cross-dams

The volume of sediment transported to the Bay of Bengal through the Lower Meghna River gives rise to natural accretion in the shallow water area of the Meghna Estuary mouth, the Sandwip area. Tides, waves, river flow and sediment supply influence the hydro-morphologic conditions in the Sandwip – Urirchar – Noakhali area. Tidal motion moves sediment originating from the Meghna estuary mouth into the Sandwip-Urirchar-Noakhali area. Velocities are considerably reduced at the tidal meeting points between Urirchar – Noakhali, Shwarna Dwip – Noakhali and Shwarna Dwip – Sandwip which results in natural sedimentation of the channel bed. Figure 2 shows the tidal meeting point around this area. This implies that there is a huge potential of land reclamation at this point accelerating natural accretion with physical interventions.

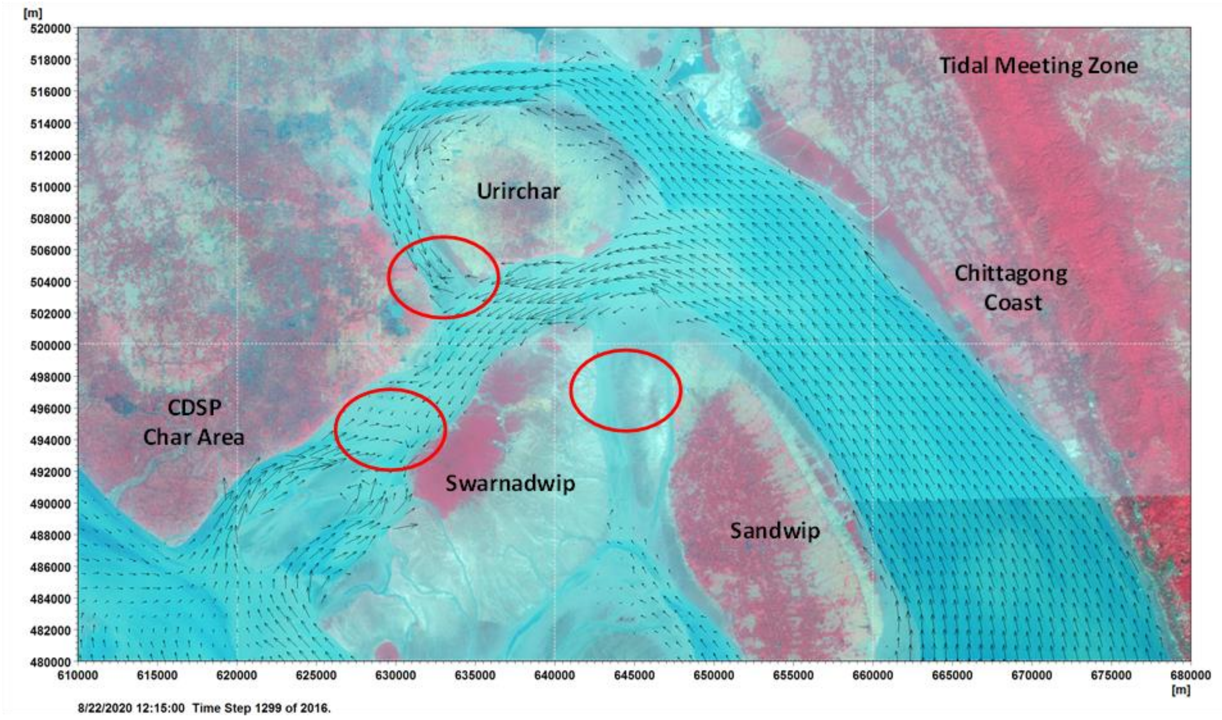

Figure 2 Tidal meeting point (red circles) around Sandwip-Urir Char-Swarna Dwip-Noakhali from hydrodynamic model result.

The Governments of Bangladesh and the Netherlands cooperated in 1977 to work on Land Reclamation Project (LRP) which continued until 1991 and focussed on reclamation and development of newly formed land. Two phases of the Meghna Estuary Study (MES) carried out extensive bathymetric surveys as well as the implementation of several erosion control and land reclamation measures on a pilot basis. Later, a Task Force of BWDB identified the location of 19 potential cross-dam locations to accelerate the natural land formation process in the Meghna Estuary on the basis of the findings and observations resulting from MES and MES-II.

The Estuary Development Project (EDP) was executed from 2007-2011 to update the bathymetric survey under the MES projects, to do an investigation and design of land reclamation measures such as cross-dams and to plan implementation. The impacts of different cross-dam combinations in south of Bhola and near Sandwip, Urir Char and Noakhali on tide, wave, drainage and erosion-deposition pattern were assessed in the study. The study recommended three cross-dams in order to accelerate natural accretion process at tidal meeting points between Urir Char, Sandwip and Shwarno Dwip presented in Figure 3. The most accretion prone area of the Meghna Estuary is Sandwip, Urirchar and Shwarno Dwip area where about 0.22m/yr deposition is found (IWM, 2010). Another study was carried out in 2013 to plan and detailed design the Urir Char–Noakhali Cross-dam and predicted that about 11,000-hectare land could be reclaimed in seven years (HaskoningDHV, 2014).

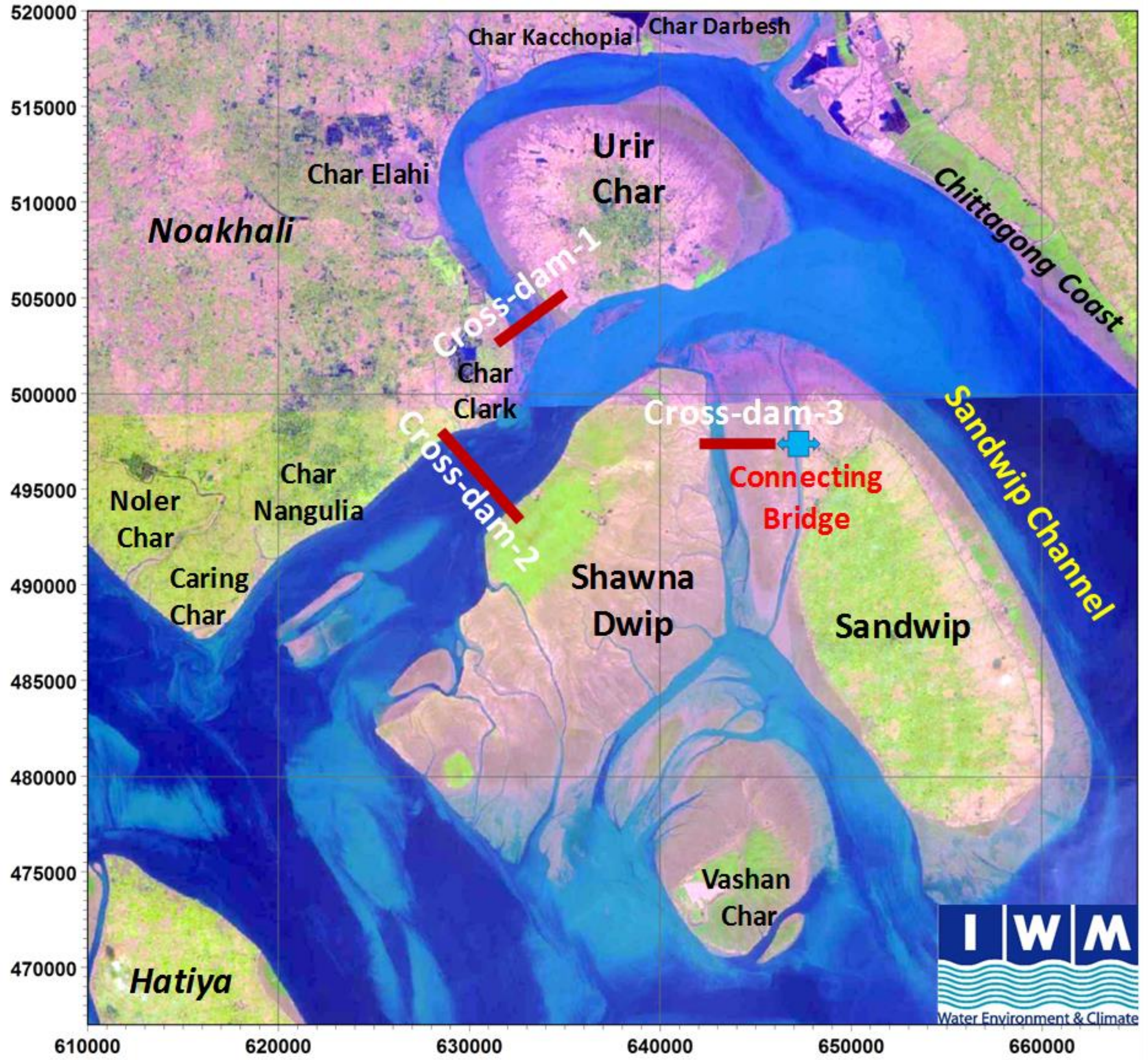

Figure 3 Proposed cross-dam locations around Sandwip-Urir Char-Noakhali recommended in EDP, 2011

In this study, we run the Lower Meghna morphodynamic model for 30 years with inclusion of two cross-dams (cross-dam-1 and cross-dam-2). We examine the effect of cross-dam for the following two scenarios:

- Effect of cross-dams with present SSC
- Effect of cross-dams with 50% reduction of present SSC

4.2.2 Dredging

Lower Meghna

The Lower Meghna River is a morphologically dynamic river. Frequent channel and submerged char movements are common scenarios. Newly developed submerged chars often divert the flow towards the land. For that reason, the mainland is often prone to serious erosion of the riverbank. To control bank erosion, channelization of the river by means of dredging is important. For proper channelization, the dredging alignment and dredging level are to be established based on the following criteria:

- The proposed dredging channel must establish a flowing channel from upstream to downstream of the dredging channel;
- Current direction;
- Required navigational depth and width of the channel;
- The dominant flow direction and availability of deeper channels;
- Current speed in the dredged channel after dredging.

Figure 4 shows the proposed location of the dredging channel at Lower Meghna river. These dredging channels are determined based on the bathymetry of year 2020. Before dredging operation there should be a pre-dredging survey and based on this the dredging alignment should be revised.

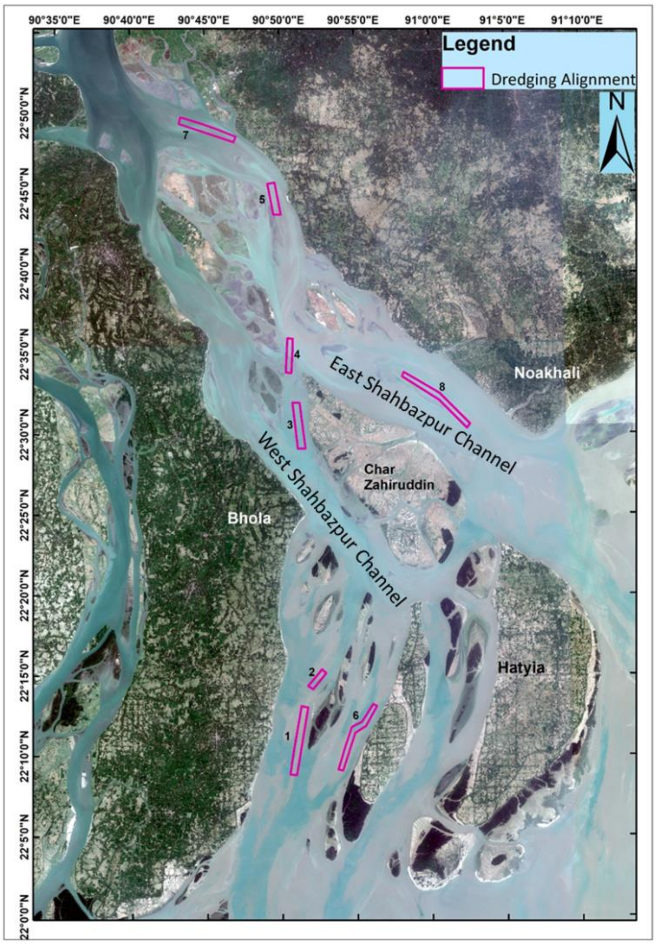

Figure 4 Proposed location of Dredging at Lower Meghna River.

Pussur

The Pussur River is an important navigation channel due to the location of one of the major ports of Bangladesh, Mongla port, situated almost 90 Km upstream from the estuary mouth. Although initially the river was much deeper during the construction of Mongla port, later the navigable depth started decreasing due to siltation. Thus, continuous maintenance dredging has been a requirement for sustaining the proper navigability of the Pussur channel. Three major capital dredging projects have been implemented in 1991-1992, 2004-2005 and 2013-2014 with dredging volumes of 3.5 Million m^3, 2.8 Million m^3 and 3.4 Million m^3 (Source: Mongla Port Authority Website) respectively for navigability of vessels around Mongla port. Another two capital dredging projects further upstream of Mongla port and Outer bar area near the coast have been implemented for Rampal power plant in 2018-2019 and 2019-2021 in order to ensure safe navigability of coal carrying vessels. The dredging volume upstream of Mongla port for in 2018-2019 was 3.47 Million m^3 and the dredging volume for outer bar in 2019-2021 was 11.91 Million m^3 (Source: Mongla Port Authority Website). Apart from these capital dredging projects regular maintenance dredging has been implemented to sustain the navigability of the Pussur river. The major dredging location of the harbour area contains several locations known as Sabur Beacon (SB), Jetty front (JF), Jetty channel (JC), Mooring Bouy (MB), Base creek (BC) area (Figure 5). As regular dredging is ongoing in the harbour area of the Pussur river, it is very important to assess the impact of these dredging works on the river morphology and also to quantify the siltation rate to some extent in order to plan any major project for future by Bangladesh government. In order to do so dredging scenarios have been incorporated in the meso-scale modelling to understand the impact of dredging on long term morphology in Pussur-Sibsa river system.

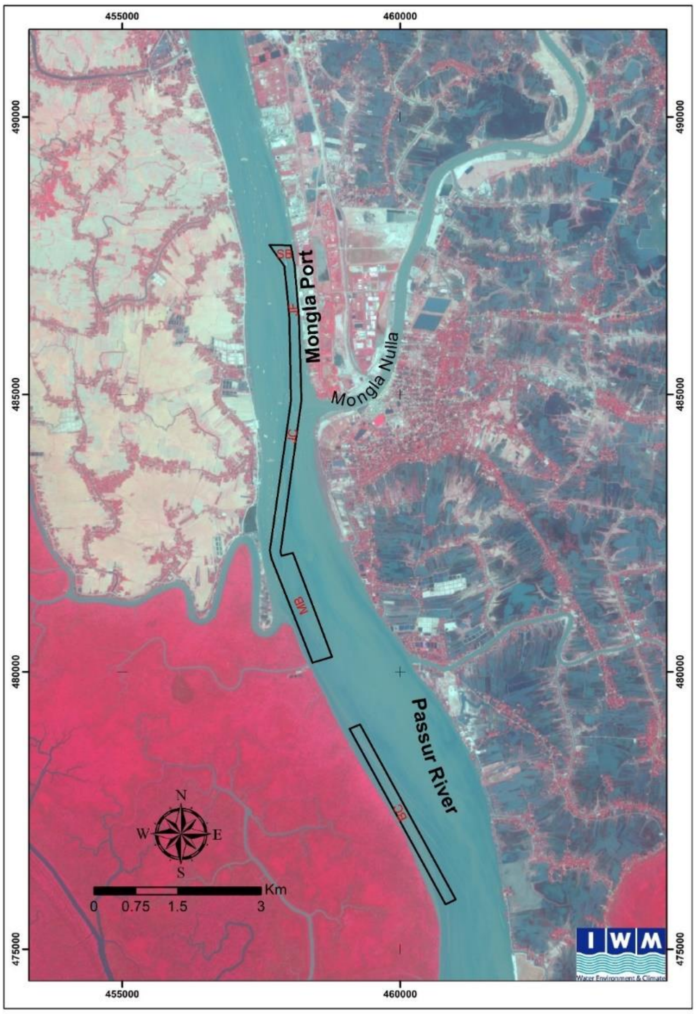

Figure 5 Dredging Alignment near Mongla Port in Pussur river

So far Mongla Port Authority (MPA) has performed several capital and maintenance dredging programs to maintain channel navigability. There were three major capital dredging projects in the harbour area and yearly maintenance project only in the jetty front area which has been incorporated in the modelling scenario. To understand the model performance with actual dredging data from MPA* (Table 4) and model result is being analysed.

Table 4 Dredging data of MPA (2022)

Dredging period	Dredging Area	Dredging Quantity (Million m³)
1979-1981	Jetty front(J5-J9)	0.325
1983-1987	Jetty front(J5-J9)	0.695
1988-1990	Jetty front(J5-J9) & Confluence	0.523
1991-1992	Harbour Area	3.551
1993-1996	Southern Anchorage confluence & Sabur Beacon	0.226
1994-2000	Jetty front (J5-J9)	0.813
2000-2004	Harbour Area	2.79
2003-2004	Jetty no- 8 & 9	0.069
2004-2005	Jetty no- 8 & 9	0.054
2005-2006	Jetty no- 8 & 9	0.069
2007-2008	Jetty no- 8 & 9	0.108
2009-2010	Jetty no- 8 & 9	0.071
2012-2013	Jetty no- 8 & 9	0.017
2013-2014	Harbour Area	3.406
2015-2016	Approach and Pontoon front of NilKomol	0.155
2017-18	Jetty Front	0.14
	Mongla Port to Rampal Power Plant	0.41
	Approach to NilKomol	0.038
2018-19	Jetty Front	0.125
	Mongla Port to Rampal Power Plant	3.47
	Approach to NilKomol	0.048
	Food Silo Area	0.125
2019-20	Outer Bar	7
	Jetty Front	0.1
	Food Silo Area	0.948
2020-21	Outer Bar	4.911
	Jetty Front	0.025
	Inner Bar	2.83
Total		**33.042**

From the table data in 1991-2000 it can be concluded that there has been one capital dredging of 3.551 million m³, after that 1993-1996 there has been dredging in Jetty channel and Anchorage of 0.226 million m³ and finally from 1994-2000 there has been dredging in Jetty front of 0.813 million m³. Data indicates that yearly average maintenance dredging in Jetty front area from 1994-2000 was 0.136 million m³. From year 2000-2004 here has been one capital dredging of 2.79 million m³ and after that from 2003-2013 there has been maintenance dredging of 0.388 million m³ only in two jetty areas (Jetty 8 and Jetty 9) giving yearly average maintenance of 0.039 million m³ only in 2 jetties. From year 2013-2014 there has been another capital dredging of 3.406 million m³ and after that from 2017-2021 there has been maintenance dredging of 0.39 million m³ giving yearly average maintenance dredging of 0.078 million m³. To summarise this from 1991-2000, total dredging volume both capital and maintenance is 4.59 million m³, from 2000-2013, total dredging volume both capital and maintenance is 3.178 million m³ and from 2013-2021, total dredging volume both capital and maintenance is 3.796 million m³. This gives yearly average dredging volume of 0.385 million m³.

5 Results

5.1 Macro-scale scenarios

5.1.1 Pussur-Sibsa

The initial bathymetry in 2020 and the modelled bed levels for No SLR (PSC1) and 1m SLR (PSC2) scenarios are presented Figure 6. Sedimentation/erosion patterns are shown in the left and middle panel of Figure 7. In this Figure, a number of subareas is defined. Positive, negative and net volume changes were calculated for each subarea. The volumetric changes for each subarea are given in Table 5. The effect of 1m SLR on bed level change between 2020 and 2050 is presented in Figure 7, right panel.

Clearly, the effects of 1m SLR by 2100, corresponding to 0.30m SLR by 2050, are quite minor, as follows from the right panel in Figure 7: differences between the scenarios are plotted at one tenth of the colour scale of the individual sedimentation/erosion patterns and then still small. Averaged over all subareas the net sedimentation increases from 352 to 362 Mm^3, a 3% increase.

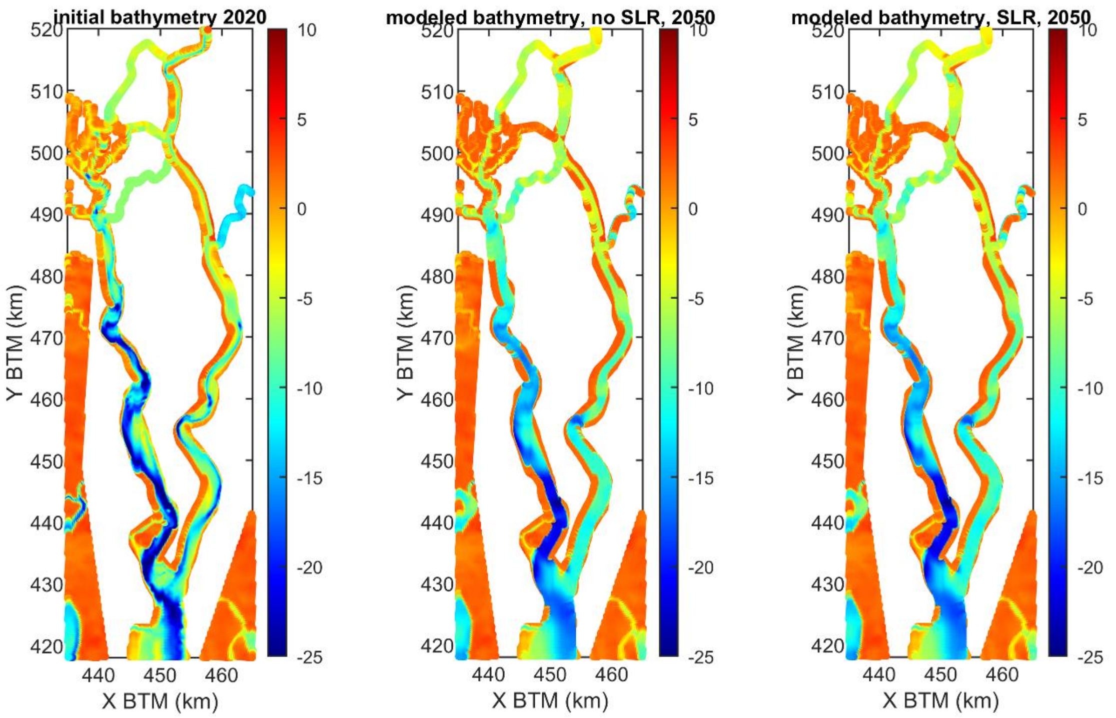

Figure 6 Initial model bathymetry in 2020, modelled bathymetry in 2050 for runs as defined in Table 5

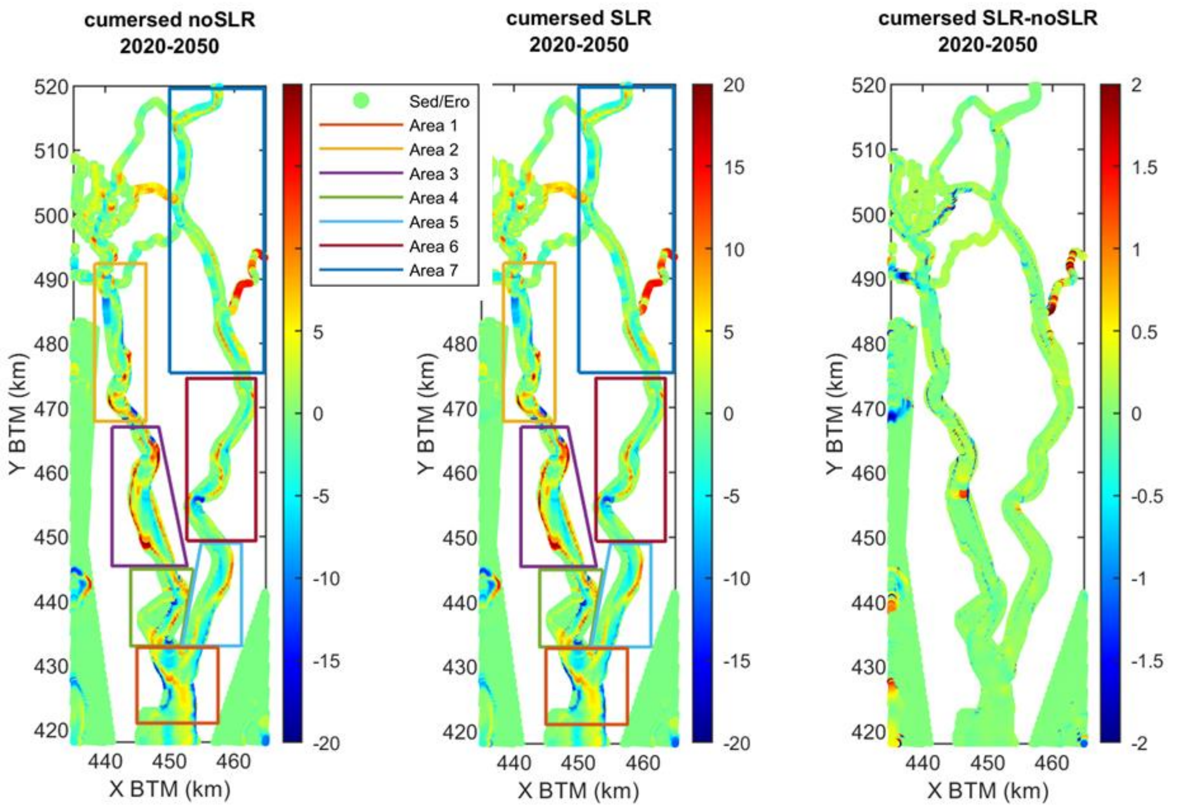

Figure 7 Sedimentation/erosion in Pussur-Sibsa system, 2020-2050. Left panel: no SLR, Mid panel: 1m SLR and Right Panel: The effect of 30 cm SLR on bed level change between 2020 and 2050. Negative values denote erosion by SLR.

Table 5 Volumetric changes for Pussur-Sibsa system under sea level rise (SLR) scenario

Area	No SLR volume change (Mm^3)			1m SLR volume change (Mm^3)		
	Erosion	Deposition	Net	Erosion	Deposition	Net
1	-65	120	55	-67	119	52
2	-55	251	196	-55	250	195
3	-62	118	56	-63	119	56
4	-77	62	-15	-76	63	-13
5	-81	94	13	-78	96	18
6	-61	130	69	-61	135	74
7	-147	125	-22	-147	127	-20
Total	***-549***	***908***	***352***	***-546***	***908***	***362***

5.1.2 Baleswar-Bishkali

The initial bathymetry in 2020 and the modelled bed levels for No SLR (BBC1) and 1m SLR (BBC2) scenarios are presented Figure 8. Sedimentation/erosion patterns are shown in the left and middle panel of Figure 9. In this Figure, a number of subareas is defined. Positive, negative and net volume changes were calculated for each subarea. The volumetric changes for each subarea are given in Table 6. The effect of 1m SLR on bed level change between 2020 and 2050 is presented in Figure 9, right panel.

Again, the effect of SLR over this time period is very small, and in this case even leads to less net sedimentation: from 38 Mm^3 to 34 Mm^3.

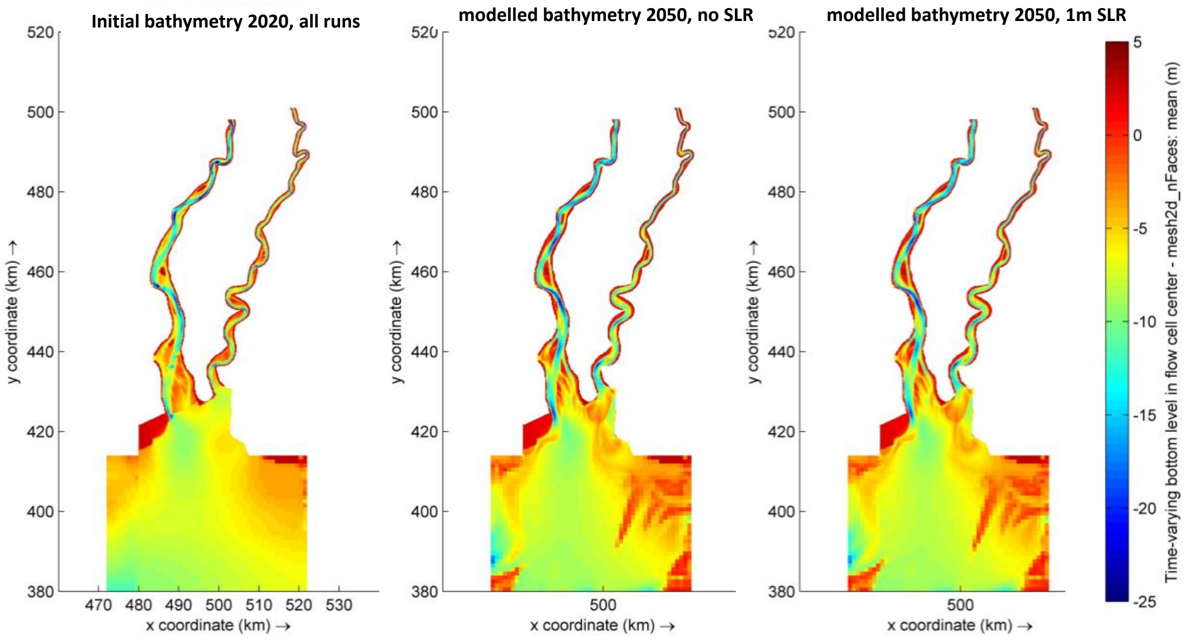

Figure 8 Initial model bathymetry in 2020, modelled bathymetry in 2050 for runs as defined in Table 6

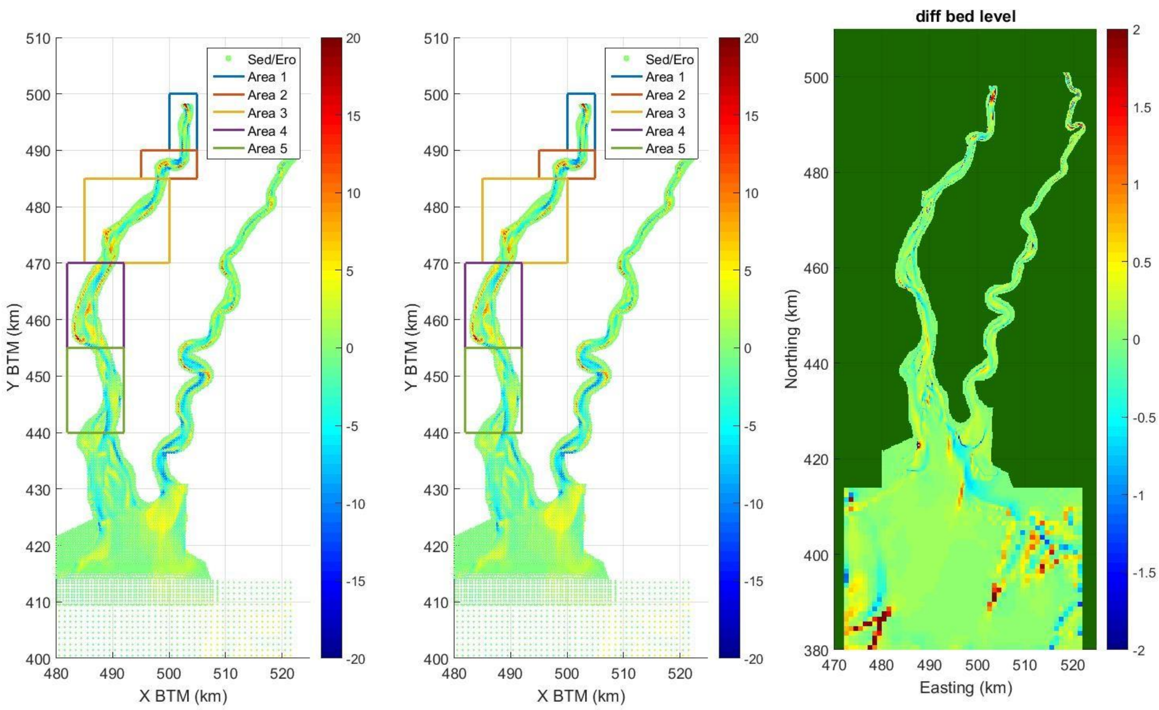

Figure 9 Sedimentation/erosion in Baleswar River, 2020-2050. Left panel: no SLR, Mid panel: 1m SLR and Right Panel: The effect of 1m SLR on bed level change between 2020 and 2050. Negative values denote erosion by SLR.

Table 6 Volumetric changes for Baleswar River under sea level rise (SLR) scenario

Area	No SLR volume change (Mm^3)			1m SLR volume change (Mm^3)		
	Erosion	Deposition	Net	Erosion	Deposition	Net
1	-21	20	-1	-22	20	-2
2	-38	28	-10	-39	28	-11
3	-62	84	23	-63	84	21
4	-67	145	78	-69	146	77
5	-101	50	-51	-101	51	-50
Total	***-290***	***328***	***38***	***-295***	***329***	***34***

5.1.3 Lower Meghna

Effect of SLR

The initial bathymetry in 2020 and the modelled bed levels for No SLR (MEC1) and 1m SLR (MEC2) are presented in Figure 10. Sedimentation/erosion patterns are shown in the left and middle panel of Figure 11Figure 9. In this Figure, a number of subareas is defined. Positive, negative and net volume changes were calculated for each subarea. The volumetric changes for each subarea are given in Table 7. The effect of 1m SLR on bed level change between 2020 and 2050 is presented in Figure 11, right panel, and more in detail for each subarea in Figure 12.

Also, in this case, the effect of SLR on the sedimentation patterns is limited, as shown in Figure 12. Over the whole area there is a net erosion, which increases with SLR, most likely due to an increased tidal range and hence tidal velocities in much of the area. In Area 4, around Uri Char, there is a large net sedimentation which increases with SLR; here, the increased accommodation space is likely responsible.

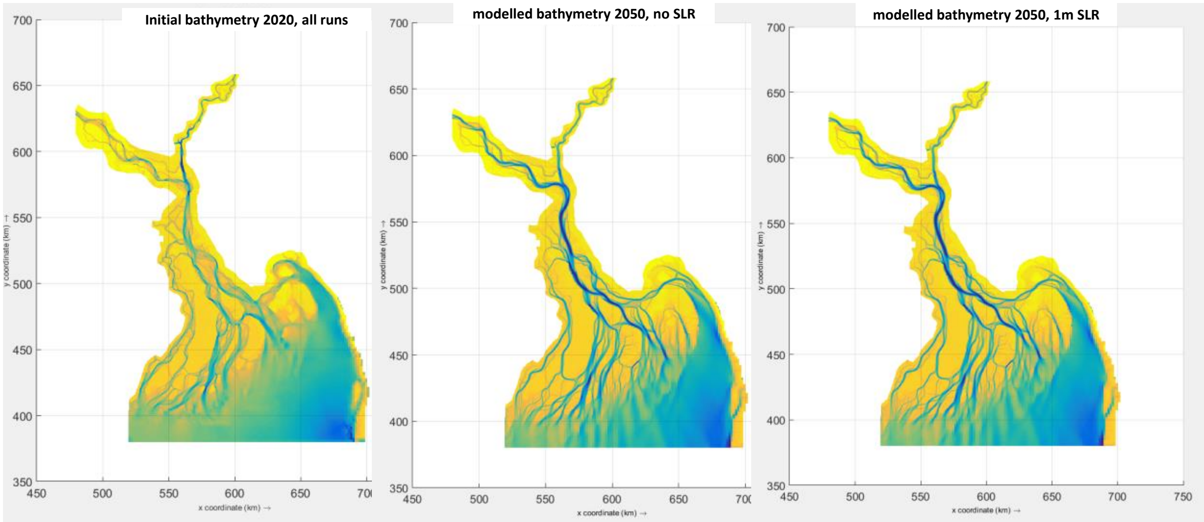

Figure 10 Initial model bathymetry in 2020, modelled bathymetry in 2050 for runs as defined in Table 7

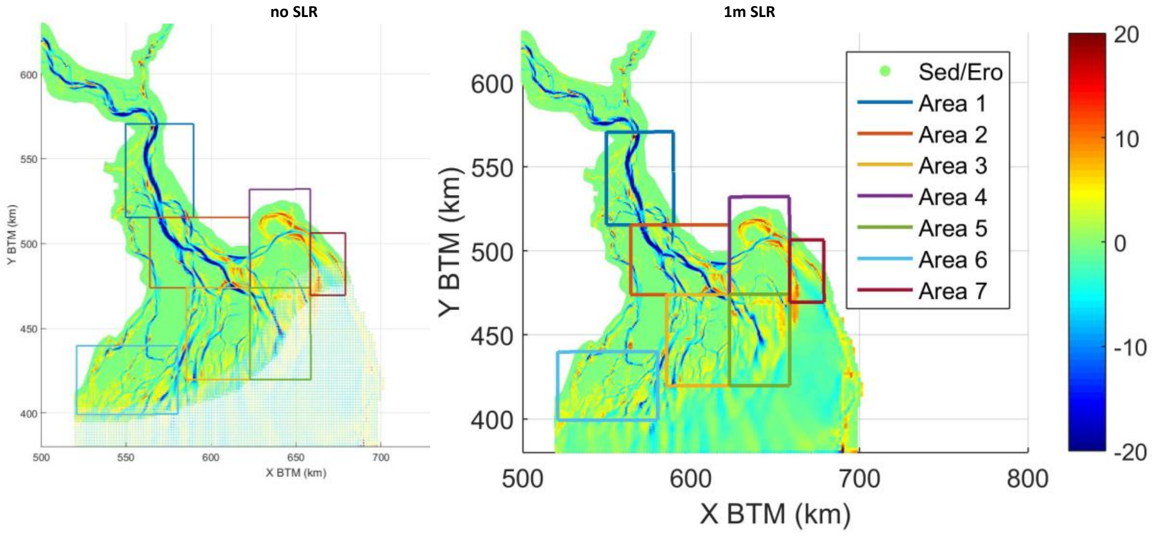

Figure 11 Sedimentation/erosion in Lower Meghna river, 2020-2050. Left panel: no SLR and Right panel: 1m SLR

Table 7 Volumetric changes for Lower Meghna River under sea level rise scenario

Area	No SLR volume change (Mm^3)			1m SLR volume change (Mm^3)		
	Erosion	**Deposition**	**Net**	**Erosion**	**Deposition**	**Net**
1	-6947	1905	-5042	-7047	1878	-5169
2	-9357	3711	-5646	-9469	3660	-5809
3	-6166	4063	-2103	-6160	4047	-2112
4	-1510	4394	2884	-1549	4465	2916
5	-4869	5731	862	-4893	5749	856
6	-3917	5010	1092	-3922	5001	1079
7	-908	2242	1334	-879	2213	1334
Total	-33676	27058	-6618	-33918	27014	-6905

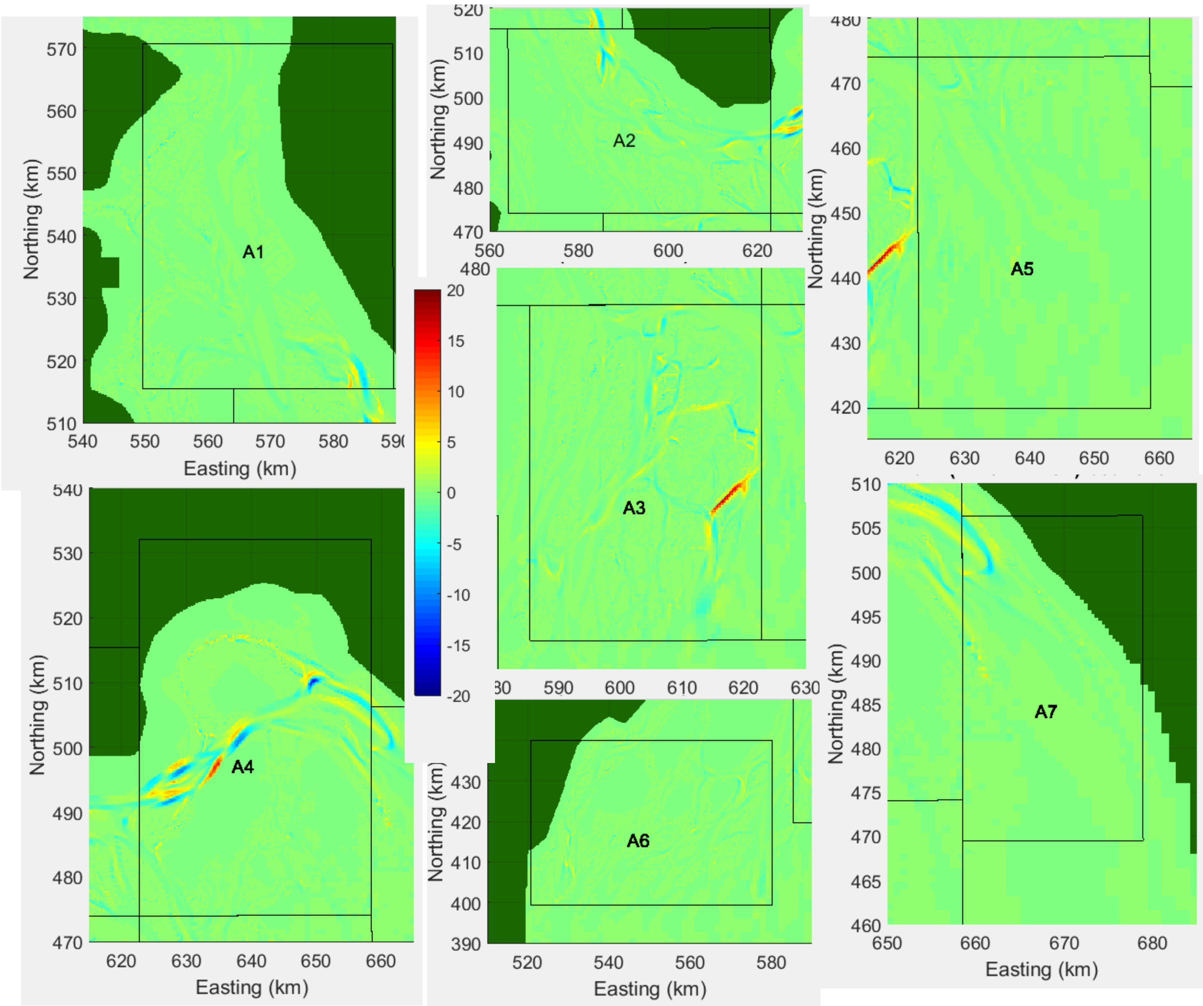

Figure 12 Effect of 1m SLR scenario on bed level change between 2020 and 2050 for each sub area

Effect of sediment supply reduction

Results of the standard run (MEC3) are compared to results of the scenario with 50% reduction of SSC at the boundary (MEC4). Sedimentation/erosion patterns are shown in Figure 13. In this figure, a number of subareas is defined. Positive, negative and net volume changes were calculated for each subarea. The volumetric changes for each subarea are given in Table 8. The effect of sediment supply reduction is considerable. Volumes in all areas decrease with smallest decrease of about 5% in areas 4 and 7 surrounding the Sandwip area and largest values almost decreasing volumes by a factor 4 (area 2) or a factor 10 (area 3).

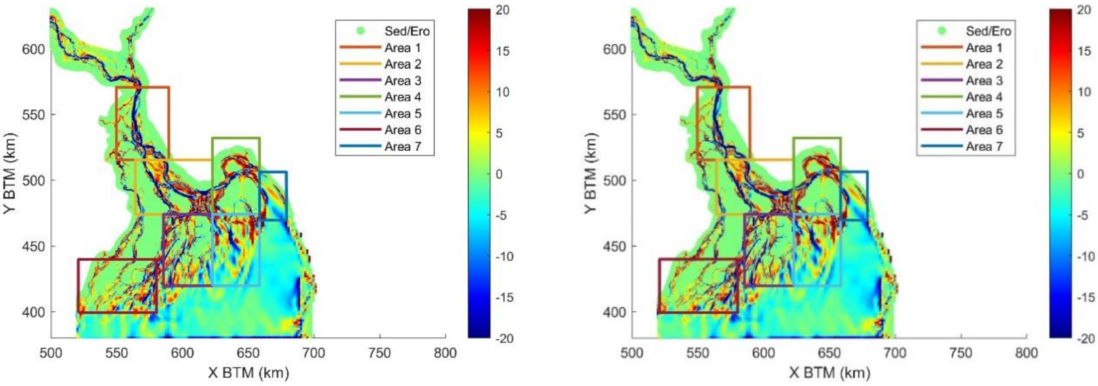

Figure 13 Sedimentation/erosion in Lower Meghna river, 2020-2050. Left panel: present SSC and Right panel: 50% reduction SSC

Table 8 Volumetric changes for Lower Meghna River for reduction SSC scenario

MEC3				**MEC4**			
Area	**Erosion**	**Sedimentation**	**Nett**	**Area**	**Erosion**	**Sedimentation**	**Nett**
1	-7166	4262	-2904	1	-7589	3587	-4001
2	-9872	9397	-476	2	-10448	8465	-1983
3	-7537	9040	1503	3	-8111	8283	172
4	-3176	7867	4690	4	-3277	7757	4480
5	-6311	8827	2516	5	-6622	8422	1800
6	-4761	7808	3047	6	-5444	7251	1807
7	-1992	2605	613	7	-1986	2545	560
Total	-40815	49805	8990	Total	-43476	46311	2834

5.1.4 Sangu

The initial bathymetry in 2020 and the modelled bed levels for No SLR (SC1) and 1m SLR (SC2) are presented in Figure 14. Sedimentation/erosion patterns are shown in the left and middle panel of Figure 15Figure 9. In this Figure, a number of subareas is defined. Positive, negative and net volume changes were calculated for each subarea. The volumetric changes for each subarea are given in Table 7. The effect of 1m SLR on bed level change between 2020 and 2050 is presented in Figure 15, right panel.

The effect of SLR is again quite limited and in this case leads to a slightly less erosive trend.

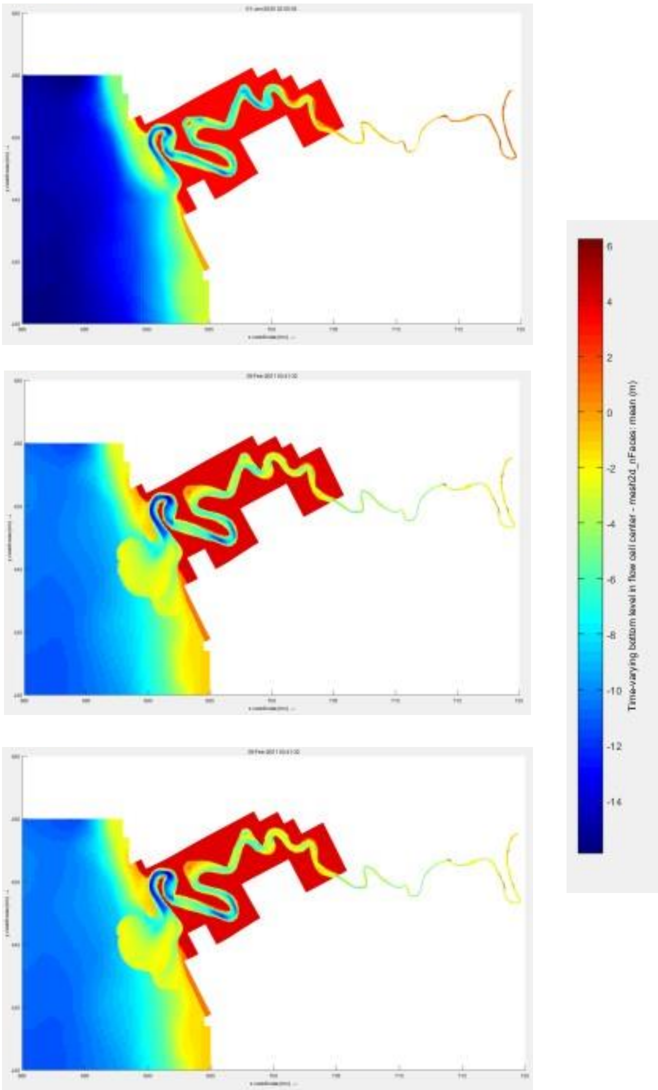

Figure 14 Initial model bathymetry in 2020, modelled bathymetry in 2050 for runs as defined in Table 8

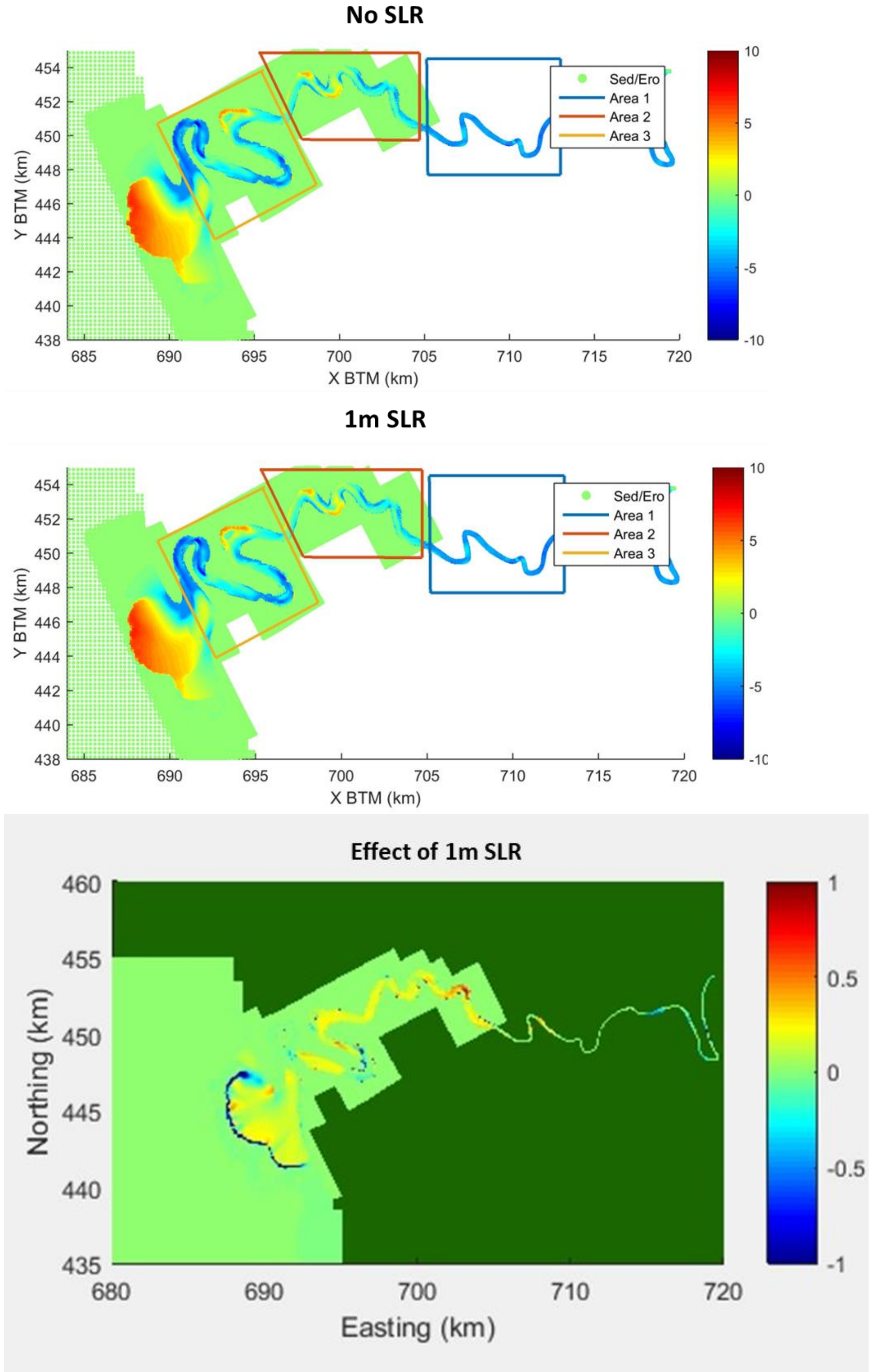

Figure 15 Sedimentation/erosion Sangu River, 2020-2050. Upper panel: no SLR and Middle panel: 1m SLR and Lower Panel: Effect of 1m SLR scenario on bed level change between 2020 and 2050

Table 9 Volumetric changes for Sangu River under different scenarios

Area	No SLR volume change (Mm³)			1m SLR volume change (Mm³)		
	Erosion	Deposition	Net	Erosion	Deposition	Net
1	-8	0	-8	-8	0	-8
2	-16	4	-12	-15	4	-11
3	-52	5	-47	-52	6	-46
Total	-77	9	-68	-75	10	-65

5.2 Meso-scale scenarios (local human interventions)

5.2.1 Lower Meghna River Model

Impact of cross-dam construction

Figure 16 illustrates the impact of the cross-dam on the eastern part of the Lower Meghna river. The results indicate a considerable impact comparable with ongoing morphodynamic development. The areas of Shwarnadwip, Urirchar, and Noakhali would merge. The southern islands Sandwip and Bhasan Char, will grow in size and join together naturally. Between the islands of Shwarnadwip and Sandwip, a new channel will develop where the tides currently meet. Figure 17 and Table 10 show that the impact of cross-dam construction is quite large in the Sandwip area. However, the impact of reduced upstream sediment supply remains limited in the Sandwip area in case of the cross-dam construction, despite the fact that other areas of the Lower Meghna are significantly affected by this reduced sediment supply scenario.

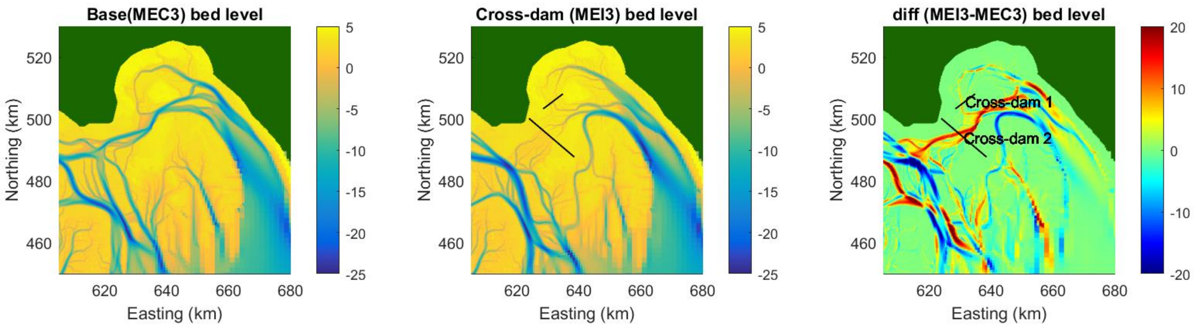

Figure 16 Effect of cross-dam with present SSC (upper panel) after 30 years and 50% reduction of present SSC (lower panel) after 30 years.

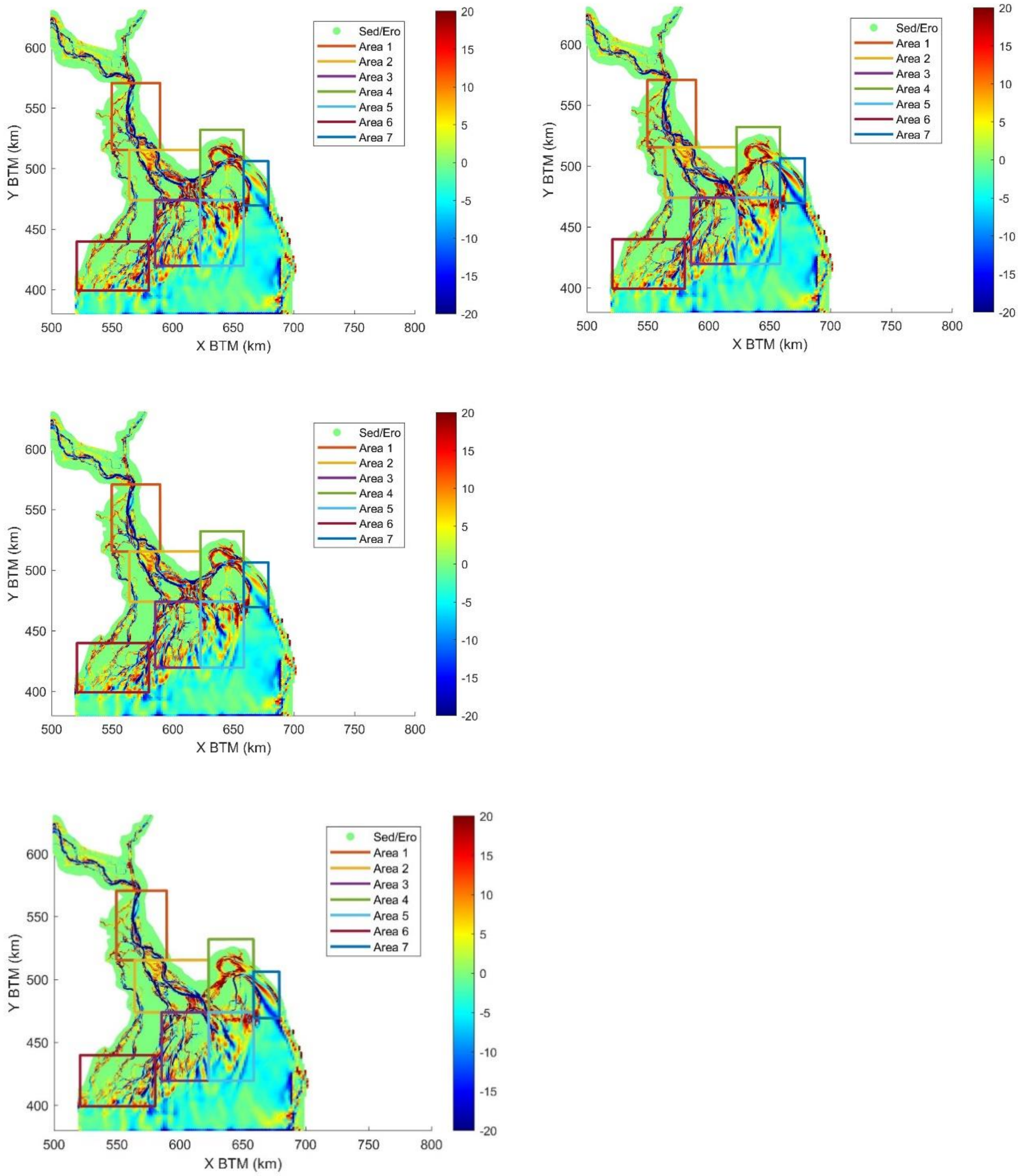

Figure 17 Erosion and sedimentation patterns of the standard run (MEC3, upper left panel) are compared to results of the scenario with 50% reduction of SSC at the river boundary (MEC4, lower left panel), the inclusion of cross-dams (MEI3, upper right panel) and the inclusion of cross-dams with reduced sediment supply (MEI4, lower right panel).

Table 10 Erosion and sedimentation volumes of the standard run (MEC3, upper left panel) are compared to volumes of the scenario with 50% reduction of SSC at the river boundary (MEC4, lower left panel), the inclusion of cross-dams (MEI3, upper right panel) and the inclusion of cross-dams with reduced sediment supply (MEI4, lower right panel).

MEC3				**MEI3**			
Area	**Erosion**	**Sedimen-tation**	**Nett**	**Area**	**Erosion**	**Sedimen-tation**	**Nett**
1	-7166	4262	-2904	1	-6698	4258	-2440
2	-9872	9397	-476	2	-9318	7916	-1402
3	-7537	9040	1503	3	-7059	8644	1586
4	-3176	7867	4690	4	-1962	8903	6941
5	-6311	8827	2516	5	-6819	8982	2162
6	-4761	7808	3047	6	-4654	6992	2338
7	-1992	2605	613	7	-3005	2970	-35
Total	-40815	49805	8990	Total	-39515	48664	9149
MEC4				**MEI4**			
Area	**Erosion**	**Area**	**Erosion**	**Area**	**Erosion**	**Area**	**Erosion**
1	-7589	3587	-4001	1	-7097	3566	-3531
2	-10448	8465	-1983	2	-9852	6991	-2860
3	-8111	8283	172	3	-7605	7808	203
4	-3277	7757	4480	4	-1991	8737	6746
5	-6622	8422	1800	5	-7071	8495	1424
6	-5444	7251	1807	6	-5282	6495	1213
7	-1986	2545	560	7	-3004	2928	-76
Total	-43476	46311	2834	Total	-41901	45020	3119

Impact of dredging
Figure 18 depicts the overall bed level (bathymetry) for dredging scenarios in the lower Meghna river. Four sub-regions contain the dredging area and the disposal areas (from Area 1 to Area 4). Figure 19 to Figure 22 depict the morphological evolution of each area following dredging and deposition for a decade. The following table outlines the configuration of dredging and disposal areas/blocks.

Table 11 Dredging and dumping blocks configuration for each area

ID	**Dredging Block**	**Dumping Block**	**Percentage of dumping from dredging block**
Area 1	Dredg 5	Dump 4	100%
	Dredg 7		100%
Area 2	Dredg 3	Dump 3	100%
	Dredg 4	Dump 2	100%
Area 3	Dredg 8	Dump 1	25%
		Dump 9	25%
		Dump 7	25%

ID	Dredging Block	Dumping Block	Percentage of dumping from dredging block
		Dump 8	25%
Area 4	Dredg 1	Dump 5	100%
	Dredg 2		100%
	Dredg 6	Dump 6	100%

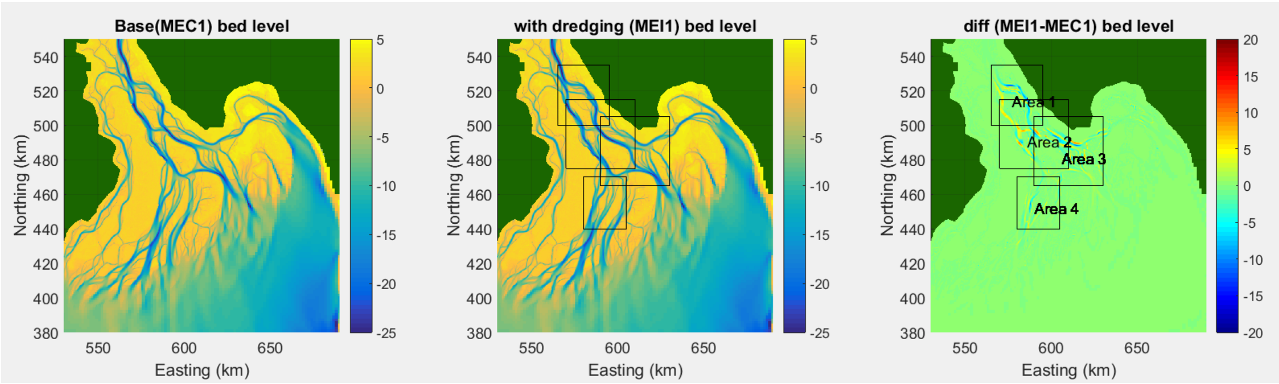

Figure 18 Effect of dredging intervention, left panel: base bathymetry 2030, mid panel: with dredging bathymetry 2030, right panel: difference in bathymetry

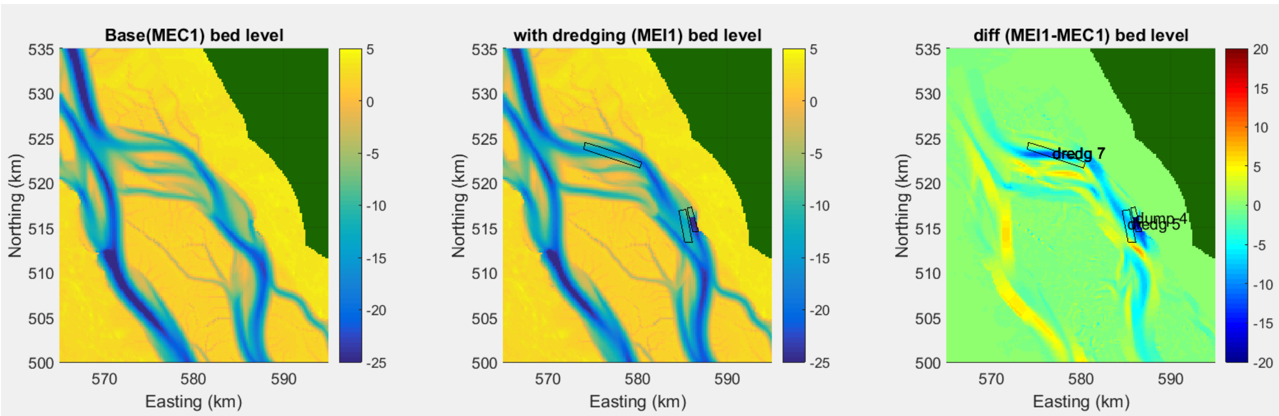

Figure 19 Effect of dredging intervention, left panel: base bathymetry 2030, mid panel: with dredging bathymetry 2030, right panel: difference in bathymetry for Area 1.

In Area 1 (Figure 19), the dredged materials from both dredging compartments/blocks (dred-5 & dred-7) are dumped in single dumping blocks (dump-4). The volume of capital dredging for dredg-5 and dredg-7 blocks is approximately 3.45 and 6.5 million cubic meters, respectively. Therefore, approximately 9.5 Mm^3 of dredging materials are being disposed of at the dump-4 block. The first-year re-siltation rate for dredg-5 blocks is approximately 3.55 Mm^3/year, while it is 5 Mm^3/year for dredg-7 blocks. After that, the re-siltation rate is reduced for the subsequent nine years. Therefore, the volume required for maintenance dredging is around 0.06 Mm^3/year for the dredg-5 block and 0.89 Mm^3/year for the dredg-7 block.

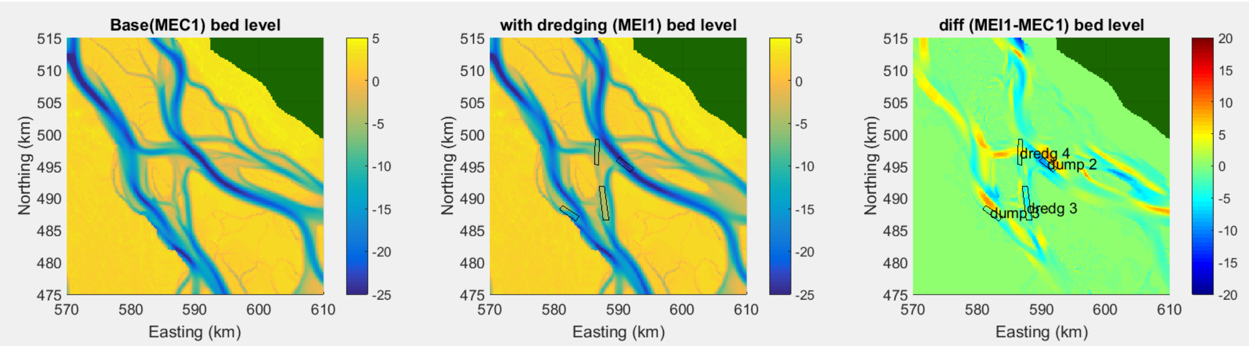

Figure 20 Effect of dredging intervention, left panel: base bathymetry 2030, mid panel: with dredging bathymetry 2030, right panel: difference in bathymetry for Area 2.

In Area 2 (Figure 20), dredging materials from dredg-4 block/compartment are dumped in dumping block dump-2 whereas, dredg-3 block is dumped in dump-3. The volume of capital dredging for the dredg-4 and dredg-3 areas/blocks is approximately 1.62 and 2.75 Mm^3 for each, respectively. For the first year, the re-siltation rate for dredg-4 blocks is approximately 6,28 Mm^3/year, which is quite high, indicating that this is not a good location for the dredging and dumping combination. After four months of capital dredging, this area is nearly filled with sediment. The rate for dredg-3 blocks is around 3.25 Mm^3/year. This indicates that this block will be filled within ten months. After that, the re-siltation rate is reduced for the subsequent nine years. Therefore, the volume required for maintenance dredging is approximately 1.34 Mm^3/year for dredg-4 blocks and 2.13 Mm^3/year for dredg-3 blocks.

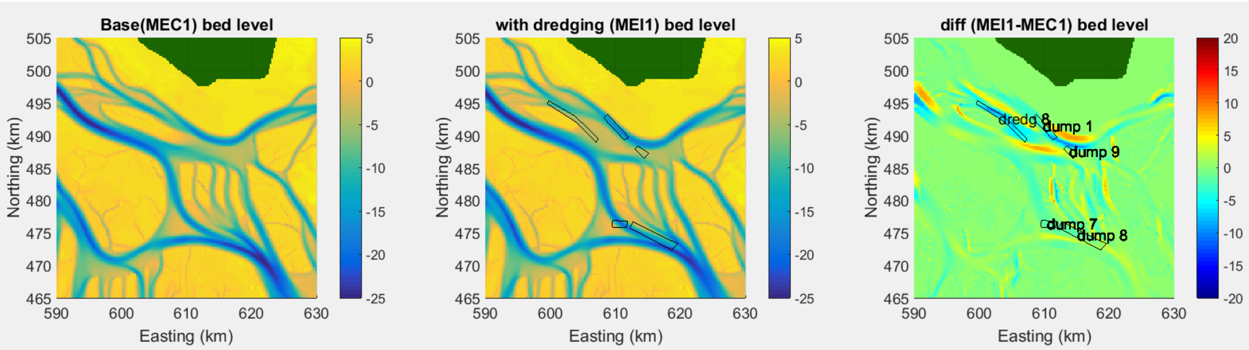

Figure 21 Effect of dredging intervention, left panel: base bathymetry 2030, mid panel: with dredging bathymetry 2030, right panel: difference in bathymetry for Area 3.

Figure 21 shows that dredg-8 is the only dredging block in Area-3, and its dredging materials will be disposed in four dumping blocks (dump 1, 7, 8 & 9). The volume of capital dredging for the dredg-8 block is approximately 5 Mm^3. Here, the total amount of dredged material is evenly distributed among the four dumping zones, or approximately 1.25 Mm^3 each block. In the first year, the re-siltation rate for this block is around 5 Mm^3/year. Therefore, after one year of capital dredging, this block is nearly filled up. The rate will climb for the subsequent nine years. Consequently, the volume required for maintenance dredging is approximately 6,67 Mm^3/year, which is extremely high.

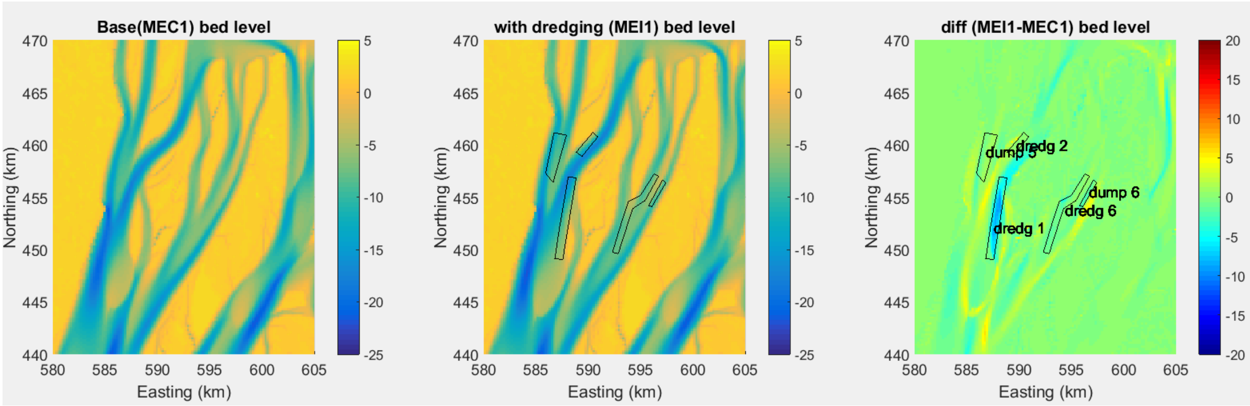

Figure 22 Effect of dredging intervention, left panel: base bathymetry 2030, mid panel: with dredging bathymetry 2030, right panel: difference in bathymetry for Area 4.

In Area 4 (Figure 22), the dredging materials from both compartments/blocks (dredg-1 & 2) are dumped in a single dumping block (dump-5), whereas dredging block-6 is dumped in dumping block-6. Blocks dredg-1, dredg-2, and dredg-6 have respective capital dredging volumes of approximately 0.5 Mm^3, 0.4 Mm^3, and 1.85 Mm^3, 0.4 Mm^3. The re-siltation rate for dredg-1 blocks is around 6 Mm^3/year for the first year and 2.61 Mm^3/year for the following nine years. Clearly, the dredg-1 area is defined in an area of char formation and goes directly against the trend; this illustrates the need to work with natural trends rather than going against them. A slight counter clockwise rotation of this dredging area could promote the growth of the southward channel at this location rather than trying to cut through the evolving char. In the first year, the re-siltation rates for dredg-2 and dredg-6 are 0.44 Mm^3/year and 1.4 Mm^3/year, respectively. For the next nine years, the needed volume for maintenance dredging is around 0.01 Mm^3/year for dredg-2 block and 0.82 Mm^3/year for dredg-6 block.

Figure 23 shows the cumulative dredging and dumping volume for each blocks/compartment for 10 years.

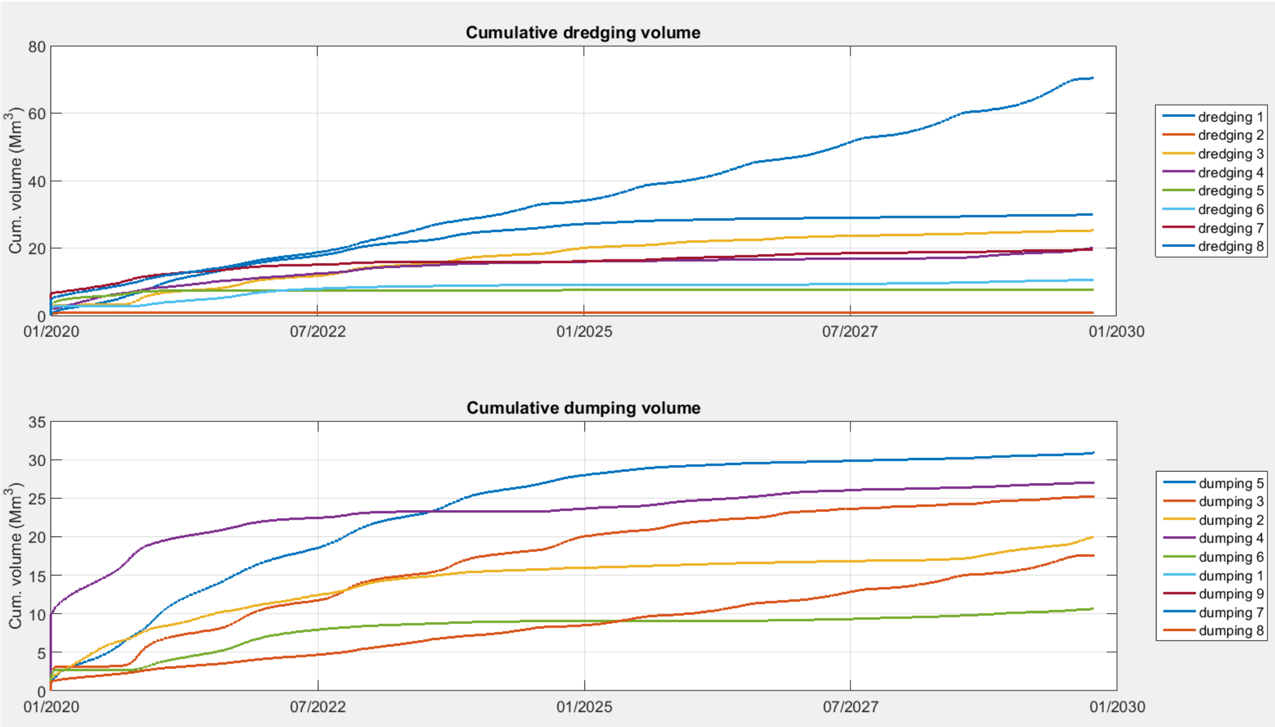

Figure 23 Cumulative dredging and dumping volume for each blocks/compartment for 10 years.

Table 12 Capital, Re-siltation rate and Maintenance volume for each dredging blocks

ID	Dredging Block	Capital dredging volume (Mm^3)	Re-siltation rate in 1st year (Mm^3)	Maintenance dredging volume next 9 year (Mm^3)
Area 1	Dredg 5	3.45	3.55	0.06
	Dredg 7	6.5	5	0.89
Area 2	Dredg 3	2.75	3.25	2.13
	Dredg 4	1.62	6.28	1.34
Area 3	Dredg 8	5	5	6.67
Area 4	Dredg 1	0.5	6	2.61
	Dredg 2	0.4	0.44	0.01
	Dredg 6	1.85	1.4	0.82

5.2.2 Pussur River Model

The model has been set up to represent the actual dredging condition for 10 years to understand the impact as well as to quantify dredging volumes for future conditions. The model dredging area is similar to the actual area only with the difference in the jetty front area. There are 5 major locations, namely Sabur beacon turning ground (SB), Jetty front (JF), Jetty channel (JC), Mooring Bouy (MB) and Base creek (BC) which are considered as harbour area according to Mongla port. In model simulations these areas are being considered to represent the actual scenario.

However, the Jetty front in the Model simulation and MPA is not same in size as to reduce complexity of the model. The Jetty front area considered by Mongla port is 50m in width from the jetty up to 900m in length with 5 jetties from Jetty 5 to Jetty 9 of equal 180m length and after 50m width up to 200m width the area known as jetty channel which goes up to mooring buoy. In the model scenario, in view of the still relatively coarse resolution, the whole 200mX900m channel is considered as Jetty front. During analysis of the comparison between model and actual data this approximation must be maintained which shows that in the model the jetty front area is 4 times the actual jetty front area and the same is true for the model result analysis. Another approximation that has been considered in the model is that the model will dredge any material that is deposited above the design bottom level and add it to the total dredging, which is not the case in the actual condition as MPA only dredges in Jetty front where most of the ship's berths are, which requires continuous design depth. This implies that the model result will be giving higher values than actual conditions albeit with same order of magnitude.

Figure 24 shows the difference of bed level to maintain the dredged channel. Apart from all the dredging area in the model, a dump area which is outside the model domain is being introduced where all the dredged material is being dumped in the model which gives the total dredging volume of the total dredged area. For individual compartments volume separate dredging volume is also plotted in Figure 25.

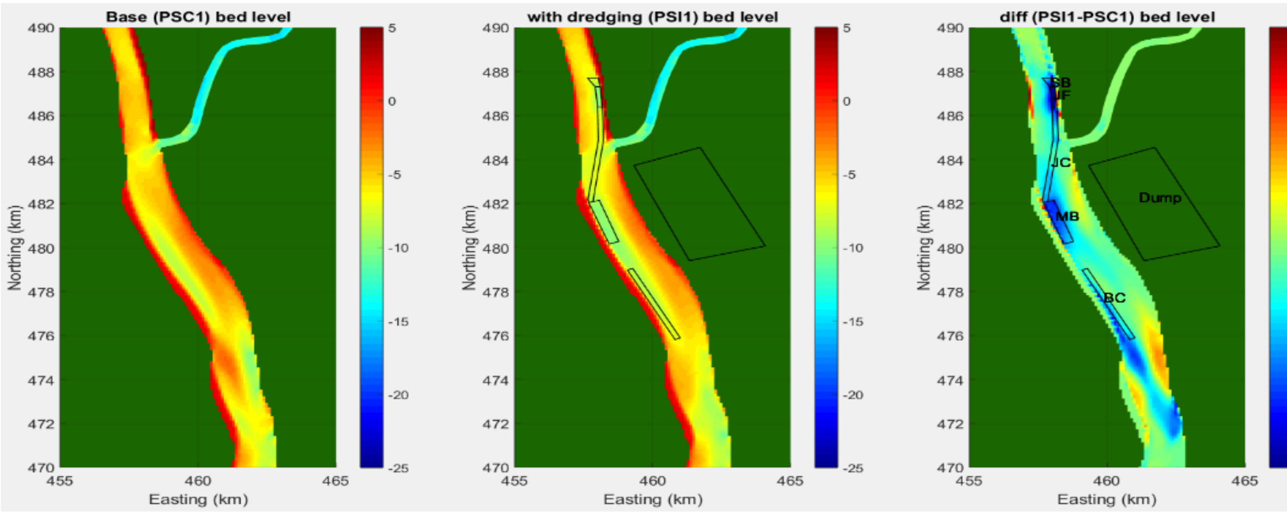

Figure 24 Difference of bed level due to dredging

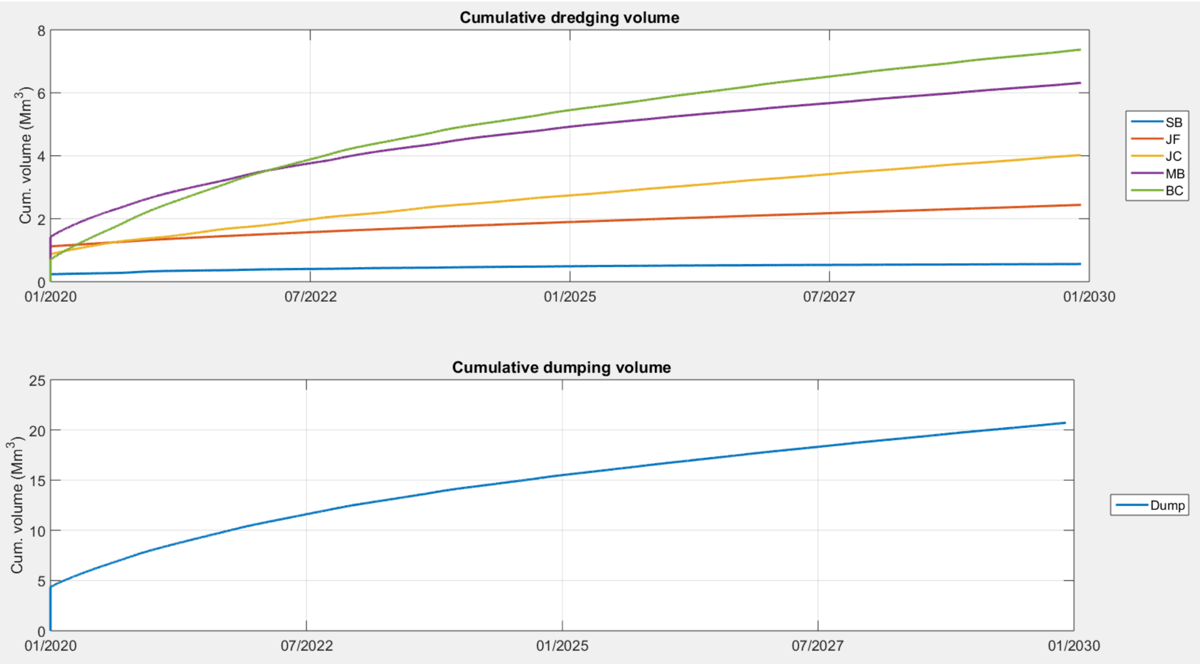

Figure 25 Dredging volume of individual area SB, JF, JC, MB & BC (upper panel) and Dumping of total dredged volume for all the areas

Figure 25 lower panel represent the total volume of all dredging areas. Initially the model starts with a capital dredging of 4.07 million m^3. After this continuous maintenance dredging of 20.7 million m^3 is seen for 10 years period which leads to 2.07 million m^3 of dredging per year. This shows that the model result is 5 times more than the actual dredging volume. The reason for this due to the approximation that is being used in the model as discussed earlier in this section. The model is dredging any siltation above the design level for the whole dredging areas keeping the design level. In the actual condition the scenario is not the same as the maintenance dredging is only done in the jetty front area where the ships are berthing and for other parts due to tidal range of about 4m, ships can pass through the channel during high tide, hence the necessity of maintenance dredging become less significant. Now, for the jetty front area model result in the upper panel of Figure 25 shows that 1.12 million m^3 of capital dredging initially and after that 1.32 million m^3 in next 9 years leads to yearly average maintenance dredging of 0.147 million m^3 per year. The model result indicates 2 times more volume than actual dredging but since the dredging area considered by MPA is less than the model result area as discussed in dredging data analysis section the dredging volume may be considered as in the same order of magnitude. The upper panel of the Figure 25 also indicates that apart from SB area all the area requires constant maintenance dredging to maintain the design depth for navigability.

6 Discussion

The net volume change in all macro-scale SLR scenarios is an order of magnitude smaller than ongoing (no-SLR) erosion and deposition volumes. This implies that, over decades, local channel-shoal patterns volume changes (eg. due to channel migration) are typically much larger than net volume changes due to SLR. Thus, the impact of SLR is difficult to distinguish by comparing bathymetries over time, because ongoing developments like channel migration govern the morphodynamic signal. SLR impact is revealed by exploring the difference in bathymetries over time of different scenarios. The observed volumetric impact of SLR remains very small to ongoing, no-SLR, morphodynamic developments. SLR induced volumetric change may be slightly smaller or larger than in case of no-SLR scenarios, depending on the system. In contrast to SLR scenarios, scenarios of reduced sediment supply in the Lower Meghna have a significant impact on the morphodynamic development.

In contrast to macro-scale scenarios, the impact of human interventions like dredging and cross-dam construction is of similar order of magnitude as ongoing (no-intervention) morphodynamic developments. The human interventions may thus locally govern channel location and shoal dynamics. Remarkably, scenarios of reduced sediment supply do not affect cross-dam construction impact in the Sandwip area. This is an example where human interventions govern the morphodynamic system.

7 Conclusions and recommendations

The current modelling study explores the 30-year impact of 30 cm SLR and human interventions on the morphodynamic development of four case studies of estuaries along the Bangladesh coast. Human intervention scenarios include current dredging practices and the foreseen construction of cross-dams in the Sandwip area for land reclamation, while SLR scenarios describe 1m/century rates and some case studies are subjected to foreseen decreasing sediment supply levels. Boundary conditions for the four meso-scale case studies are derived from an earlier macro-scale modelling study including SLR and sediment supply scenarios.

Model results show considerable but realistic morphodynamic development due to migration of channel-shoal patterns. The net volumetric effect of SLR is typically an order of magnitude smaller than erosion and sedimentation volumes due to ongoing pattern migration. For all case studies, the impact of SLR on volumetric changes is generally an order of magnitude smaller than in cases without SLR. The impact of reduced sediment supply is much larger. Human interventions have a pronounced, but local impact on the allocation of channels and shoals that is larger than SLR impact.

Future studies may explore longer time scales with increasingly larger impact of SLR, the local effects of wind waves or the local impact of 3D flow patterns (density difference driven flows). An interesting question relates to when the impact of SLR will exceed the impact of human interventions.

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