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)

Pussur-Sibsa morphological modelling study – Current situation

Joint Venture of DHI & Deltares in association with IWM, Bangladesh and University of Colorado, Boulder and Columbia University

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November 2020

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University of Colorado, Boulder, USA
Columbia University, USA

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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

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

The main objective of the “long-term monitoring, research and analysis of the Bangladesh coastal zone” project is to create a framework for polder design, based on understanding of the long-term and large-scale dynamics of the delta and sustainable polder concepts. The modelling work within the project is carried out to improve our understanding of the long-term and large-scale dynamics of the Ganges-Brahmaputra-Meghna (GBM) delta. The knowledge on sediment dynamics, distribution, erosion-deposition processes and sediment management at present and in the future under climate change, land use changes and proposed interventions in the upstream reaches of the Ganges-Brahmaputra river systems are essential for the framework of polder design.

The cascade of models applied considers three different spatial and temporal scales:

- Macro-scale: annual sediment balance of the Bengal part of the GBM delta, and long-term morphodynamics. This scale is necessary to get a comprehensive understanding on how the system functions as a whole and to estimate the impact of climate change and anthropogenic works in a general context.
- Meso-scale: regional river and estuary dynamics, driven by seasonal fluctuations in forcing conditions. This scale will highlight meandering and other dynamics of main estuarine branches and how they respond to major changes in tidal volumes, translating the macro scale findings into relevant impacts on local polder level.
- Micro-scale: water-logging and polder management. This scale is necessary to provide a detailed and local reference of (future) boundary conditions for dedicated polder design and management.

This report describes the development, calibration, validation and application of a meso-scale morphodynamic model covering the Pussur-Sibsa river system. Model results are compared to observations of water levels, discharges and suspended sediment concentrations as well as observed decadal timescale morphodynamic development in the Pussur-Sibsa system.

Meso-scale model domains have already been selected based on available previous data, erosion history and the peripheral rivers around the polders that covers the whole coastal area. CEIP officials also agreed to the selected zones for this modelling. The selected meso-scale modelling groups are the following and are reported upon in separate reports (Figure 1.1):

- **Pussur – Sibsa River system (Polder 32 & 33)**
- Baleswar – Bishkhali River system (Polder 35/1, 39/1, 39/2, 40/1, 40/2, 41 & 42)
- Lower Meghna - Tetulia River system (Polder 56/57,55/1,55/2, 55/3 & 59/2)
- Sangu River system (Polder 63/1a, 63/1b & 64/1b)

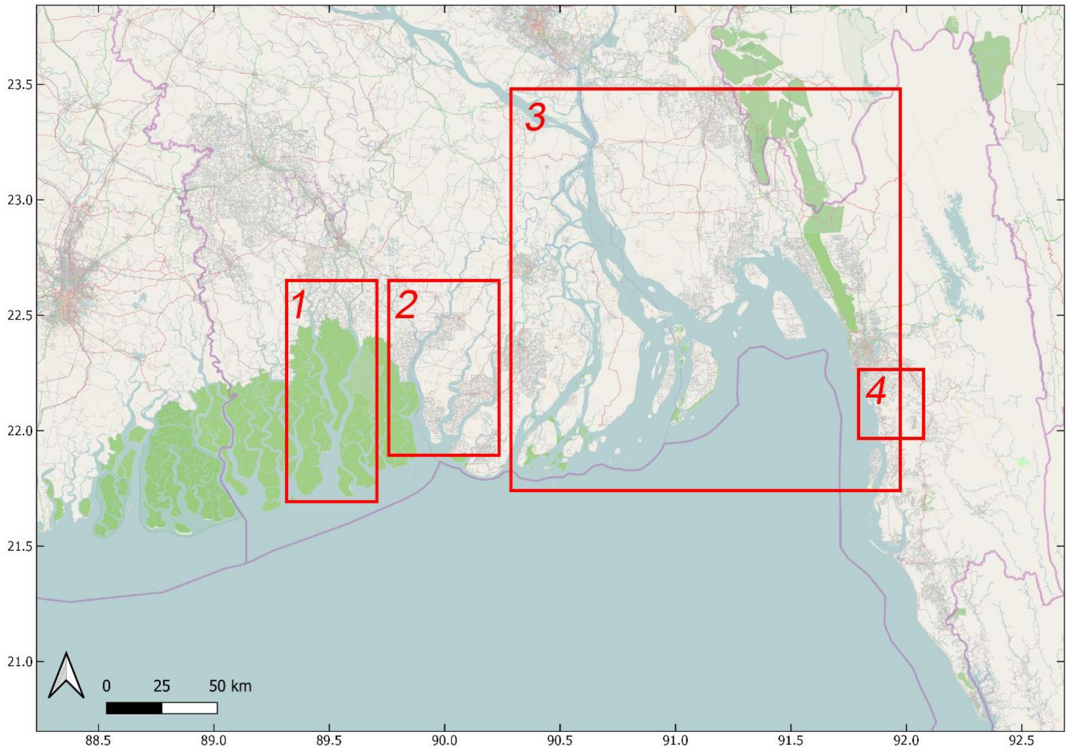

Figure 1.1 Map of meso-scale modelling groups for long-term morphology. (1) Pussur-Sibsa; (2) Baleswar-Bishkhali; (3) lower Meghna-Tetulia; (4) Sangu

2 Objectives and Approach

The objectives of this model are:

- To hindcast and predict the morphological development of the Pussur-Sibsa river system on decadal scales: can we understand the major morphological changes, what processes drives them and how will these change under future scenarios of climate change and anthropogenic interventions? This report will focus on the morphodynamic hindcast.
- To provide boundary conditions in terms of large-scale bed elevation change and sediment concentrations to micro-scale models.

The approach is as follows:

- Model grid - to construct an unstructured-grid model (Delft3D FM) of the entire Pussur-Sibsa river system, with curvilinear grid cells except where areas of different resolution are connected by triangles (this report).
- Setup and Calibration – setup, calibrate and validate the model with field measurements and remote sensing data (this report).
- Morphological hindcast – reproduce the morphology from different previous periods (this report).

- Scenario runs - study future changes in the morphodynamic processes based on possible scenarios (upcoming report).

  Two types of morphodynamic simulations are carried out:

  - Short-term (~ 1 year) runs with realistic time series boundaries;
  - Long-term (5-100 year) runs with schematized *representative* boundary conditions for the river discharges and simplified *representative* tidal components, combined with a *morphological factor* approach to accelerate the morphodynamic simulations.

Calibration of the sediment model on the shorter time scale is carried out using available sediment concentration measurements, for selected periods where bathymetric, hydrodynamic and sediment concentration measurements are available.

Calibration of the decadal-scale morphological development is carried out using the accelerated approach.

It must be noted that having a good calibration for sediment concentrations for the short-term runs is no guarantee that the same settings will lead to good morphological behaviour. This is in part because the longer-term evolution is influenced by parameters that have little influence on short time-scales, but also because there are different paths towards a reasonable concentration distribution that may result in quite different sedimentation/erosion patterns.

Therefore, the chosen approach for calibrating the sediment and morphology behaviour consists of trying to reconcile the settings for both types of simulations, rather than adopting the settings resulting from the short-term sediment calibration and assuming them to be equally valid for the morphological runs.

3 Data

In this section all used data for the model development will be documented and briefly described. This includes bathymetries, measured water levels, discharges and suspended sediment concentrations

The projection is BTM (Bangladesh Transverse Mercator) and the vertical datum is PWD (Public Works Datum).

3.1 Bathymetry

The river system has been surveyed in previous years, so suitable bathymetry information was readily available. A very detailed bathymetry survey was conducted in 2011 for the Pussur-Sibsa river system from the GRRP project. A similar bathymetry survey was conducted for the present project. The bathymetries and associated changes 2011-2019 are shown in the Figure 3.1.

Table 3.1 Bathymetry data for Pussur-Sibsa River 2011 and 2019

Bathymetry data collection year	Sources
2011	IWM (GRRP Project)
2019	Primary data (Present Project)

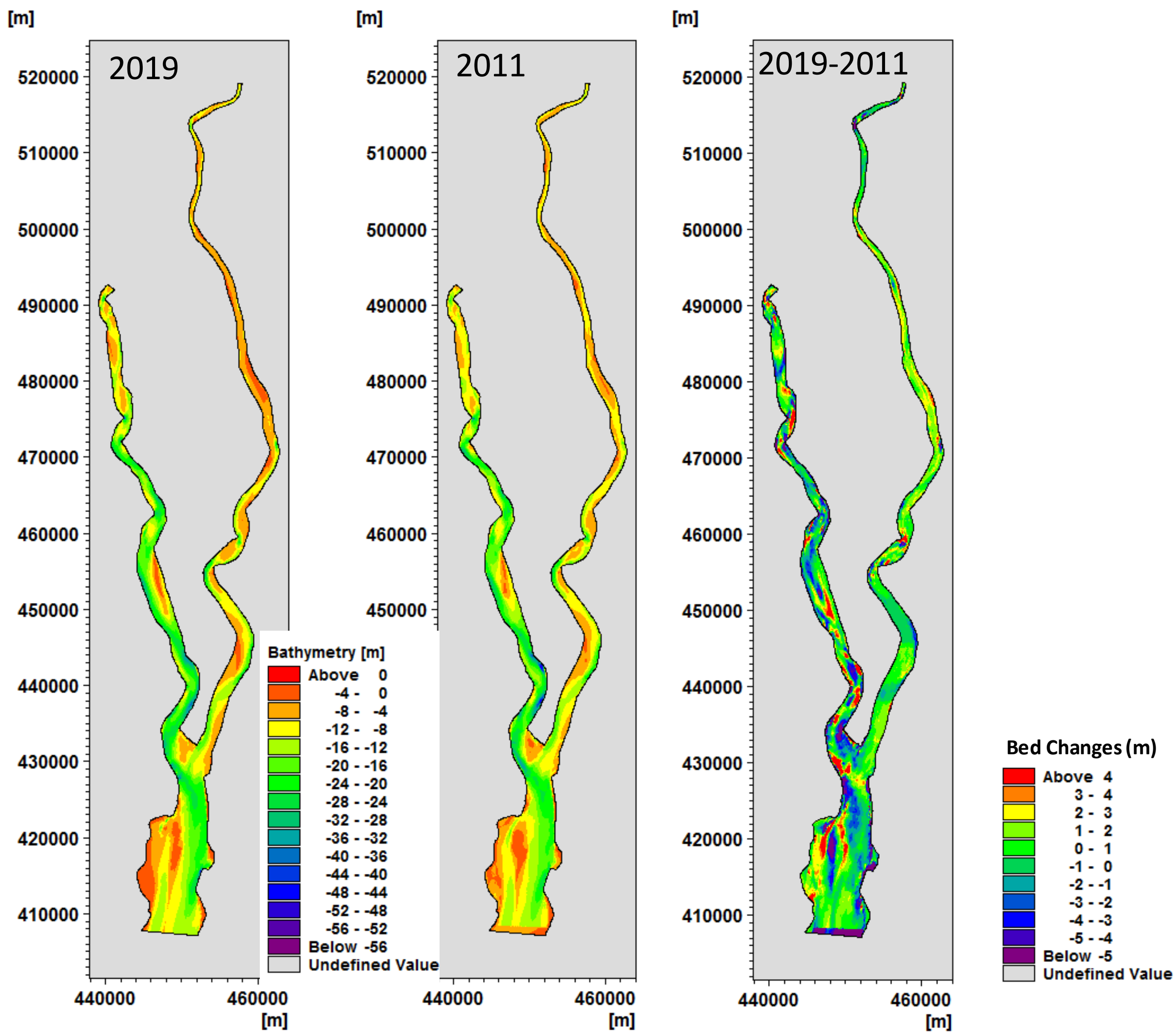

Figure 3.1 Bathymetry and bed level changes 2011-2019, from left: 2019 bathymetry, 2011 bathymetry, bed level changes 2011-2019

3.2 Digital Elevation Model (DEM)

The use of satellite derived topography maps ensured full coverage of the coastal zone of Bangladesh. A digital elevation model (DEM) dataset was acquired by FINNMAP (a Finnish consultancy firm) 1993-94.

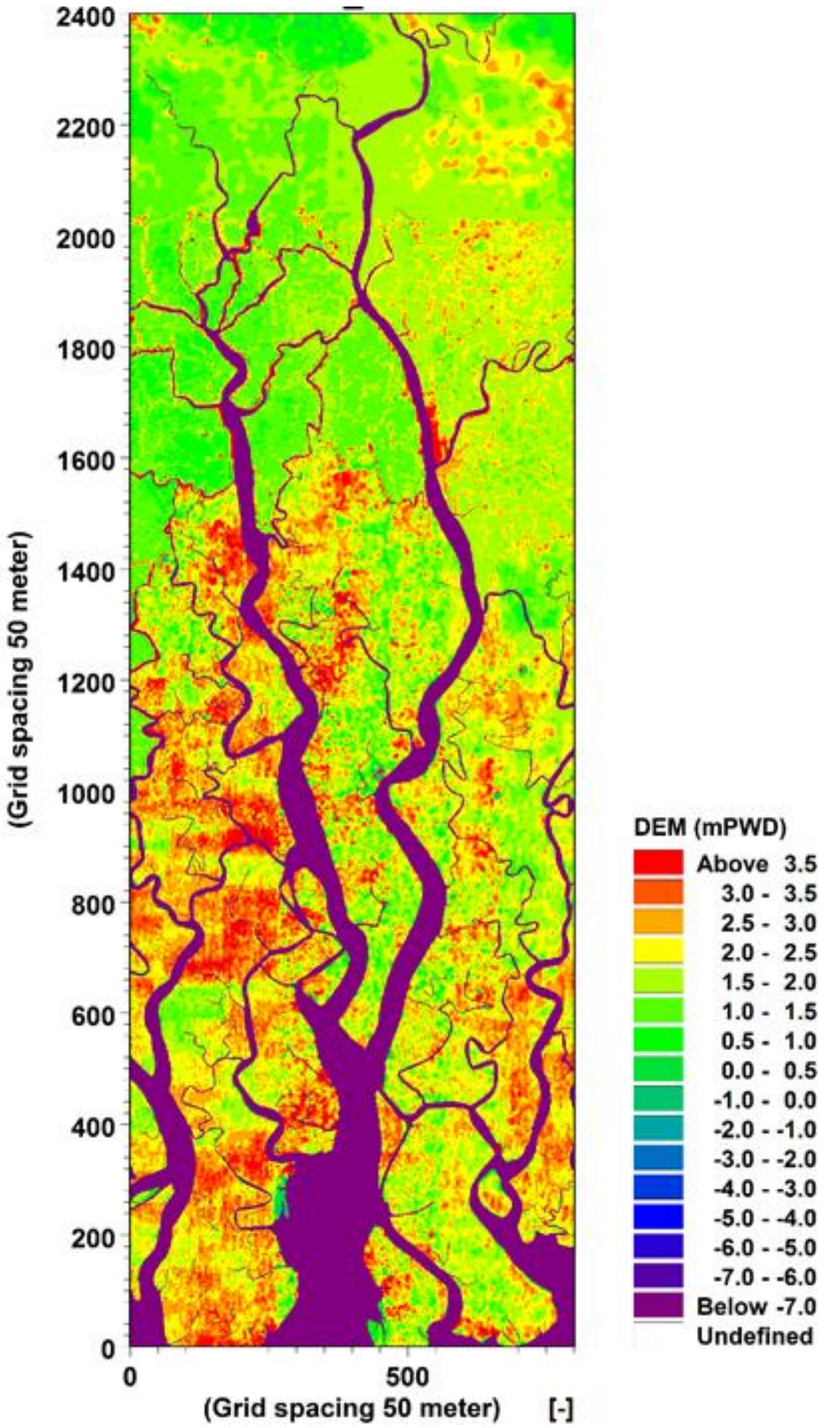

Figure 3.2 DEM (1993-94) shown as raster around Pussur-Sibsa river system

3.3 Water level time-series

Water level data is available for Mongla at Pussur river and Nalian at Sibsa river. The water level time series from different sources for the Pussur-Sibsa river system are summarised in Table 3.1. Figure 3.3 shows the measured stations of the water level data.

Table 3.2 Available water level observations from Pussur-Sibsa river system

WL collection year	Station Name	River	Sources
2011	Mongla	Pussur	IWM (GRRP Project)
2015	Nalian	Sibsa	CEIP-1 Project
2019	Mongla	Pussur	Primary data (Present Project)
	Nalian	Sibsa	

3.4 Discharge time series

Discharge time series from different sources for the Pussur-Sibsa river system are summarised in Table 3.3. Figure 3.3 shows the measured stations of the discharge data.

Table 3.3 Available discharge observations from Pussur-Sibsa river system

Discharge collection year	Station Name	River	Sources
2011	Mongla	Pussur	IWM (GRRP Project)
	Akram Point	Pussur	
	Nalian	Sibsa	
	Akram Point	Sibsa	
2016	Rupsa	Pussur	CEIP-1 Project
	Mongla	Pussur	
	Nalian	Sibsa	
2019	Mongla	Pussur	Primary data (Present Project)
	Nalian	Sibsa	

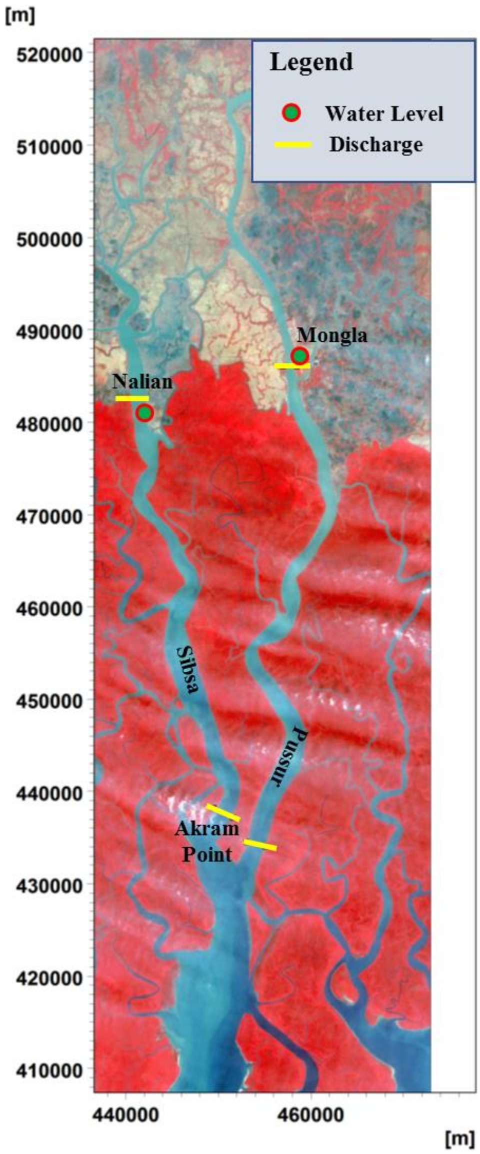

Figure 3.3 Field data collection map for campaigns from 2011, 2015, 2016 and 2019 in Pussur-Sibsa river

3.5 Sediment bed samples

In this section all readily available sediment bed samples for the Pussur-Sibsa river system have been compiled. Many samples have been collected for various projects, but no report compiling the available data into a comprehensive picture of the sediment bed could be found. Table 3.4 summarises the available data sets.

Table 3.4 Available bed samples for Pussur-Sibsa river system.

Bed sample data collection year	Sources
2011	IWM (GRRP Project)
2016	CEIP-1 Project
2019	Primary data (Present Project)

Table 3.5 Compiled bed samples inventory for Pussur-Sibsa river system from projects listed in Table 3.4. Values indicate mass percentages

ID	X	Y	Year	Name	D50 (mm)	Clay	silt	Very Fine Sand	Fine Sand	Medium Sand	SUM	Cohesive	Non-cohesive
1	457115	491756	2011	Pussur_LB_02	0.032	7.17	77.95	7.00	6.49	1.40	100.00	85.11	14.89
2	456727	491480	2011	Pussur_MD_02	0.026	8.59	81.35	8.19	1.70	0.17	100.00	89.94	10.06
3	456190	491349	2011	Pussur_RB_02	0.027	9.15	90.29	0.56	0.00	0.00	100.00	99.44	0.56
4	456190	491349	2011	Pussur_LB_182	0.025	14.54	84.76	0.70	0.00	0.00	100.00	99.30	0.70
5	456877	458065	2011	Pussur_MID_182	0.132	0.00	11.48	34.68	52.21	1.63	100.00	11.48	88.52
6	456154	458907	2011	Pussur_RB_182	0.037	7.61	90.83	1.56	0.00	0.00	100.00	98.44	1.56
7	454955	433992	2011	Pussur_LB_318	0.027	7.52	90.78	1.70	0.00	0.00	100.00	98.30	1.70
8	454478	434175	2011	Pussur_MID_318	0.123	0.00	12.06	39.05	39.82	9.07	100.00	12.06	87.94
9	453210	434624	2011	Pussur_RB_318	0.024	14.22	85.22	0.56	0.00	0.00	100.00	99.44	0.56
10	452491	415919	2011	Pussur_LB_395	0.018	10.35	87.66	1.99	0.00	0.00	100.00	98.01	1.99
11	449513	415656	2011	Pussur_MID_395	0.169	0.00	7.42	7.55	81.07	3.95	100.00	7.42	92.58
12	445979	416066	2011	Pussur_RB_395	0.015	20.50	77.34	2.16	0.00	0.00	100.00	97.84	2.16
13	452916	491747	2019	Pusur_1B_RB	0.044	5.82	86.88	4.12	2.66	0.52	100.00	92.70	7.30
14	453074	497682	2019	Pusur_2B_RB	0.043	7.74	77.33	9.43	4.43	1.06	100.00	85.07	14.93
15	456985	492018	2019	Pusur_1B_LB	0.048	8.10	70.51	12.84	6.80	1.75	100.00	78.61	21.39
16	453243	497824	2019	Pusur_2B_CL	0.058	5.12	54.53	22.70	14.52	3.13	100.00	59.65	40.35
17	440969	479694	2019	Shibsha_1B_RB	0.049	7.84	77.07	8.57	5.67	0.85	100.00	84.91	15.09
18	442300	479831	2019	Shibsha_1B_LB	0.049	7.98	72.13	12.06	6.45	1.37	100.00	80.11	19.89
19	440272	485419	2019	Shibsha_2B_RB	0.036	10.83	82.61	4.85	1.33	0.37	100.00	93.45	6.55
20	459415	481365	2016	Pussur_LB	0.027	5.68	84.94	4.88	2.97	1.54	100.00	90.62	9.38
21	458725	481396	2016	Pussur_CL	0.043	4.72	89.38	2.90	2.19	0.82	100.00	94.10	5.90
22	458065	480895	2016	Pussur_RB	0.035	11.71	85.41	2.88	0.00	0.00	100.00	97.12	2.88

ID	X	Y	Year	Name	D50 (mm)	Clay	silt	Very Fine Sand	Fine Sand	Medium Sand	SUM	Cohesive	Non-cohesive
23	442113	484068	2016	Shibsa_LB	0.021	18.33	78.79	2.88	0.00	0.00	100.00	97.12	2.88
24	441201	483925	2016	Shibsa_CL	0.032	10.50	77.73	5.93	4.16	1.68	100.00	88.23	11.77
25	440355	483961	2016	Shibsa_RB	0.043	9.18	83.80	3.32	2.65	1.06	100.00	92.98	7.02
26	457536	483888	2011	Pussur_RB	0.014	17.17	81.08	1.74	0.00	0.00	100.00	98.26	1.74
27	458421	484070	2011	Pussur_LB	0.101	0.00	13.80	52.21	24.67	9.32	100.00	13.80	86.20
28	440559	482364	2011	Nalianala_RB	0.008	45.13	54.53	0.33	0.00	0.00	100.00	99.67	0.33
29	442171	483359	2011	Nalianala_LB	0.017	13.14	85.56	1.29	0.00	0.00	100.00	98.71	1.29

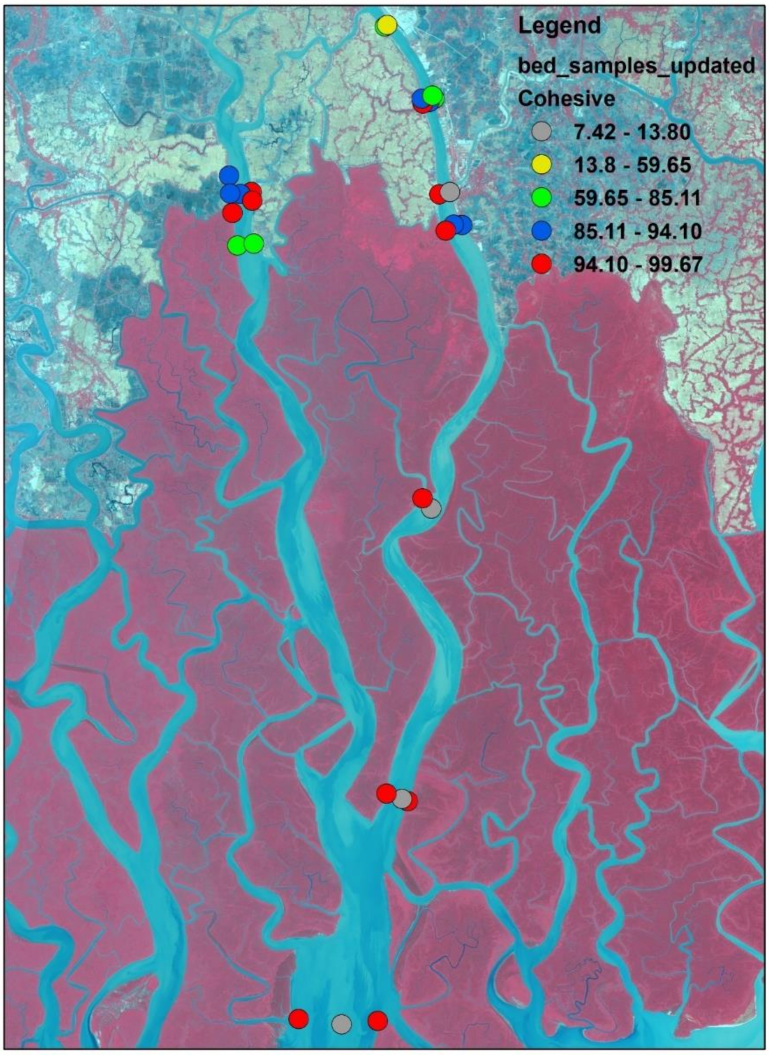

Figure 3.4 Measured sediment fraction of bed samples taken in the Pussur-Sibsa river system. The colours indicate the cohesive sediment content in mass %

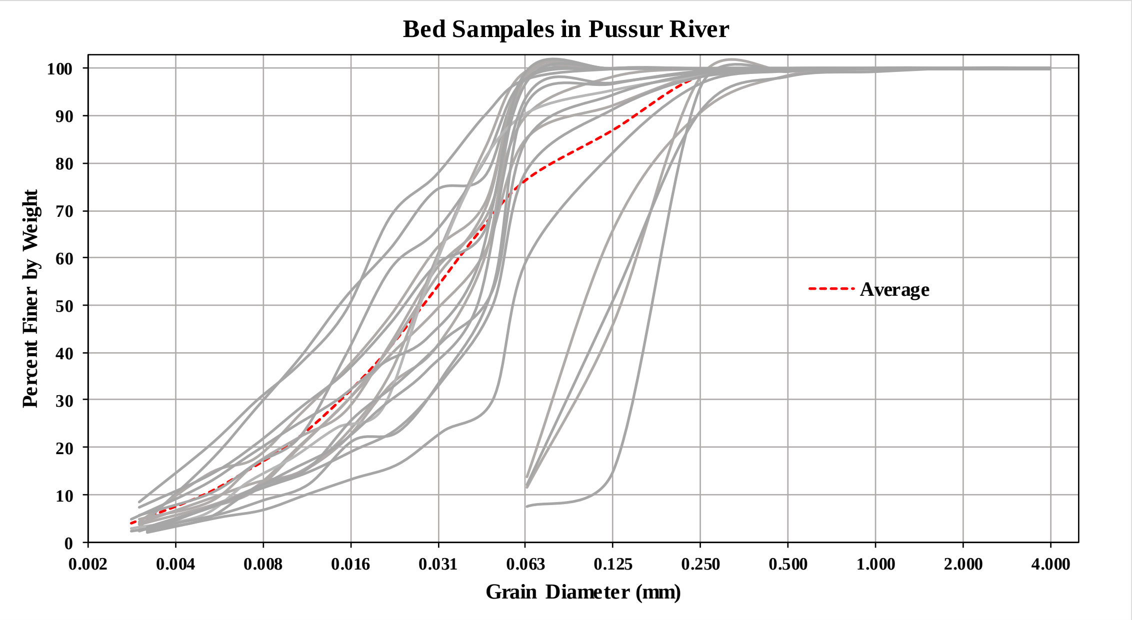

Figure 3.5 Bed samples from 2011 to 2019 (February) with average curve for Pussur river

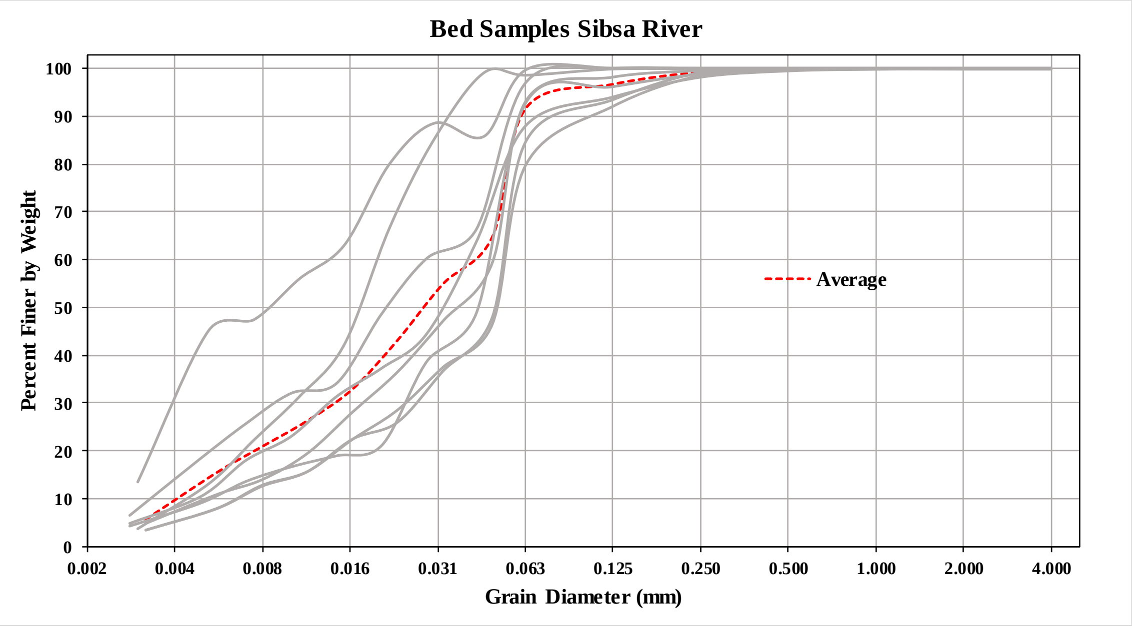

Figure 3.6 Bed samples from 2011 to 2019 (February) with average curve for Sibsa river

The available bed samples for Sibsa river show consistently cohesive sediment dominated by silt. For Pussur river, a consistent sandy composition in the river can be found, which is believed to be traced to the Gorai river. The Sibsa river does not have a clear connection to Gorai River, hence the difference in bed characteristics.

3.6 Suspended sediment data

Suspended sediment data is available at the three stations also used for hydrometric data, i.e. Nalian, Mongla and Akram Point. Table 3.6 shows the inventory of suspended sediment concentration data for the Pussur-Sibsa river system. The data collected in 2019 are sampled in February and early March and are representative of dry conditions.

Table 3.6 Suspended sediment concentration data for Pussur-Sibsa River system

SSC collection year	Station Name	River	Sources
2011	Mongla	Pussur	IWM (GRRP Project)
	Akram Point	Pussur	
2016	Mongla	Pussur	CEIP-1 Project
	Nalian	Sibsa	
2019	Mongla (8m depth)	Pussur	Primary data (Present Project)
	Nalian (15m depth)	Sibsa	

4 Model development

4.1 Grid and bathymetry

The Pussur-Sibsa river system is modelled in one numerical grid, combining both river systems in a single model. The river system is influenced by interaction with the adjacent floodplains (e.g. mangrove forest and outside the polder area) as the bed level is relatively low around this area and flooding occurs. Therefore, the floodplain was incorporated on both sides of the rivers only around 250m on each side in the numerical grid. The available 2011 bathymetry data for the main river channel was interpolated on the unstructured curvilinear grid system. Figure 4.1 shows the grid and bathymetry for the Pussur-Sibsa river system.

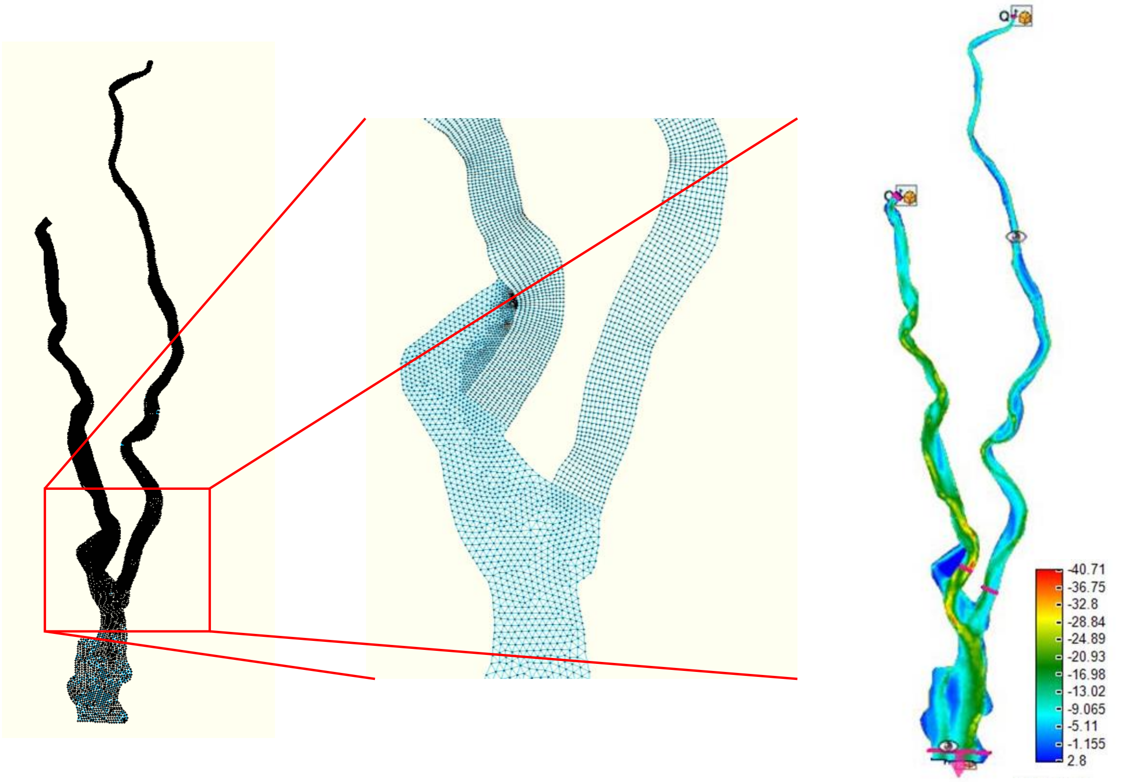

Figure 4.1 Computational mesh and interpolated bathymetry for the Pussur-Sibsa river system

4.2 Boundary conditions (hydrodynamic model)

The Pussur-Sibsa model has two upstream boundaries and one downstream boundary. Upstream boundaries have been extracted from the calibrated and validated South West Regional Model. The downstream boundary conditions are derived from measured water levels at Hiron Point.

Discharges from the side channels are implemented as additional boundaries in this model. The side channels are essential to include in the hydrodynamic model, as the flow exchanges with these side channels are significant. Without the side channels, it becomes challenging to get the correct discharges in the Pussur-Sibsa model. All the boundaries were extracted from the South West Regional Model. Figure 4.2 shows all boundaries locations in both rivers.

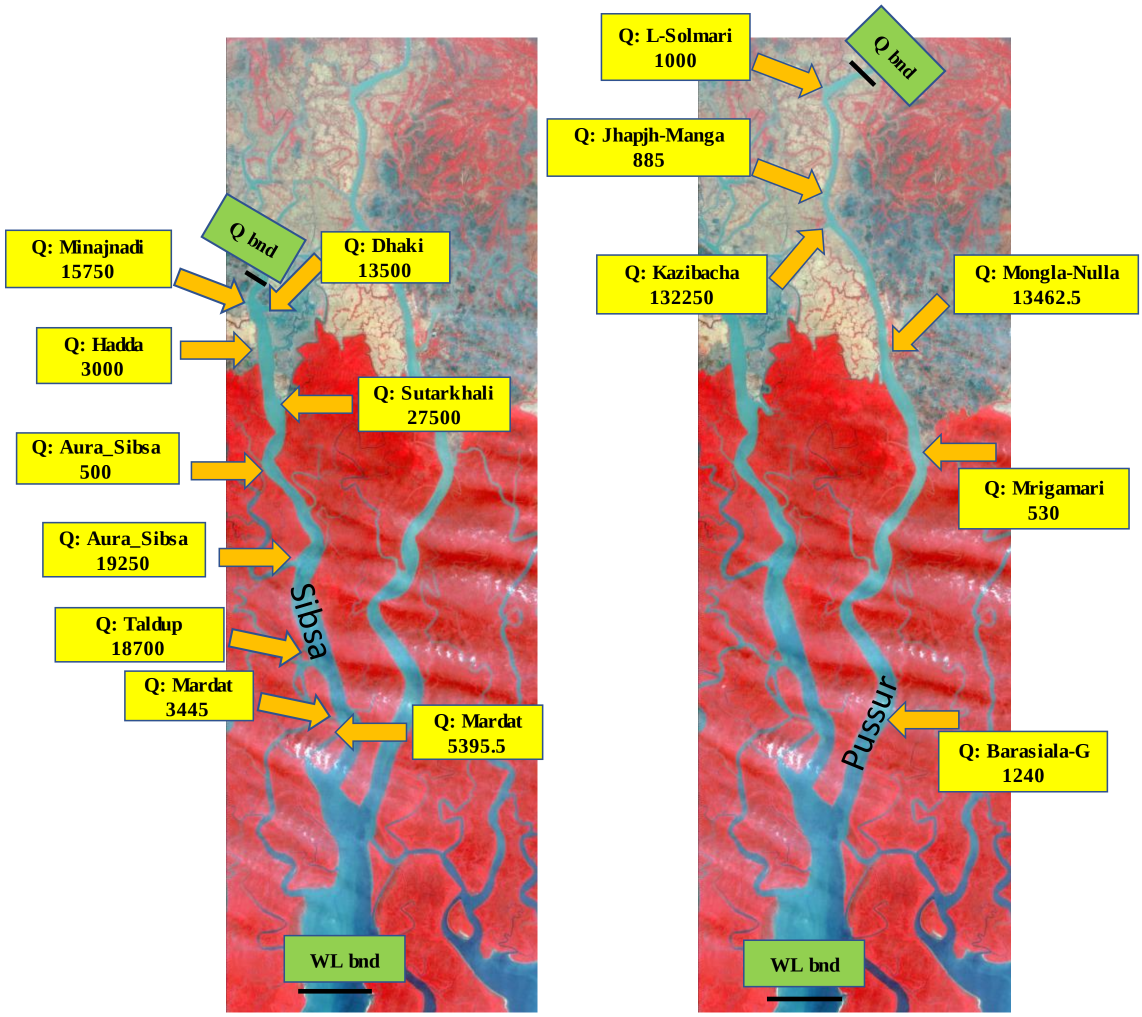

Figure 4.2 Boundaries location map in the Pussur-Sibsa river system. (yellow box indicate discharge from side channels from SWRM model chainage)

4.3 Bed resistance

From the bed sediment samples, it can be derived that the Pussur-Sibsa river system is largely cohesive in nature. However, after numerous calibration runs (section 4.4), we used a constant manning's number (n=0.017) for the whole model domain.

4.4 Hydrodynamic calibration and validation

The Delft3D FM sediment transport model calculates transport rates on a flexible mesh (unstructured grid) covering the area of interest based on hydrodynamic data obtained from a simulation with the Hydrodynamic Module (HD) as well as with information about the characteristics of the bed material. This means that a well calibrated and validated hydrodynamic model is needed to develop a reliable sediment transport model. The hydrodynamic model was calibrated and validated with field data from the 2011 measurement campaign, both for dry and monsoon season respectively. The locations of the field data sampling points are shown in Figure 3.3.

4.4.1 Calibration and validation for discharge during 2011 monsoon and dry season

Table 4.7 and Table 4.8 show the calculated error metrics for the calibration (monsoon period) and the validation (dry period), respectively. Errors in discharge magnitude for the validation periods are around 10% of the discharge amplitude, which is deemed acceptable.

Table 4.7 Error metrics discharge calibration 2011 monsoon period

		Mongla		Akram-Pussur		Akram-Sibsa	
Metric	**Unit**	**spring**	**neap**	**spring**	**neap**	**spring**	**neap**
ME	[m^3/s]	-720	-710	-577	-1327	862	-1167
MAE	[m^3/s]	2462	1132	5006	3932	10452	5405
RMSE	[m^3/s]	2802	1435	6579	5017	12841	7056
R^2	[-]	0.8237	0.9288	0.8881	0.9056	0.9137	0.9279
Nash-Sutcliffe E	[-]	0.6613	0.8840	0.8544	0.8984	0.7733	0.8678
Index of Agreement	[-]	0.9326	0.9732	0.9669	0.9729	0.9575	0.9724

Table 4.8 Error metrics discharge validation 2011 dry period

		Mongla		Akram-Pussur		Akram-Sibsa	
Metric	**Unit**	**spring**	**neap**	**spring**	**neap**	**spring**	**neap**
ME	[m^3/s]	559	522	-184	434	1800	-312
MAE	[m^3/s]	3365	1067	5267	3487	4955	2217
RMSE	[m^3/s]	4057	1427	7596	4176.	5589	2681
R^2	[-]	-	0.8281	0.8237	0.9106	0.4404	0.4766
Nash-Sutcliffe E	[-]	-1.4531	0.7710	0.8230	0.9004	0.40435	0.4664
Index of Agreement	[-]	0.1875	0.9367	0.9464	0.9711	0.4791	0.4924

Figure 4.3 to Figure 4.5 show the discharge calibration and validation at Mongla Port during monsoon and dry season. The computed discharge amplitude is underpredicted, especially during flood flow. This may be due to upstream boundary condition from the South West Regional Model. Another reason is the lack of tidal prism in the flood plain which could have retained more water volume during the flood flow. As the error is within reasonable bounds, this is not considered a major shortcoming in the model at this point.

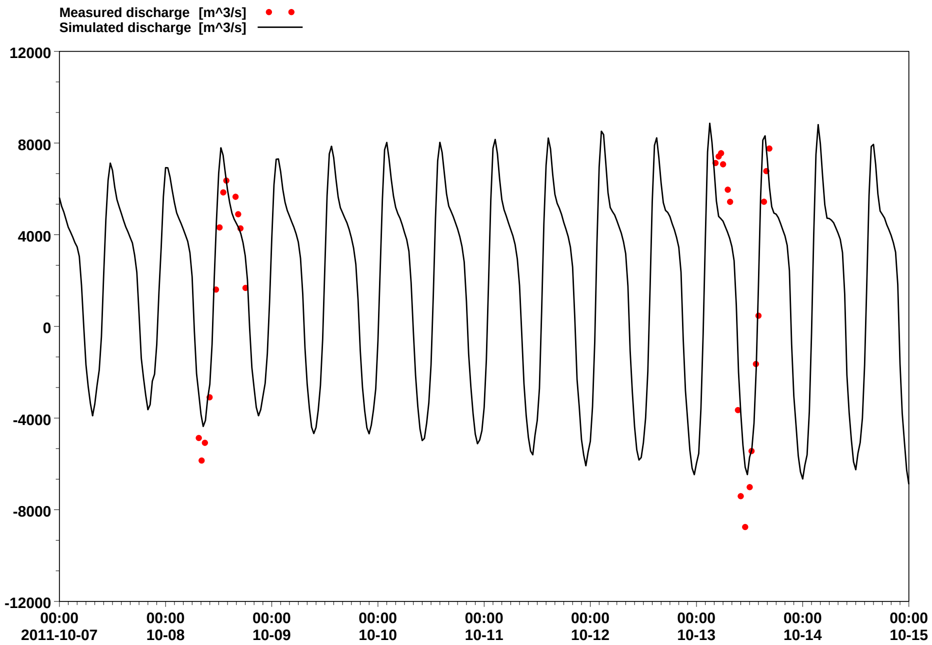

Figure 4.3 Discharge calibration at Mongla Port during Monsoon (ebb is positive, and flood is negative)

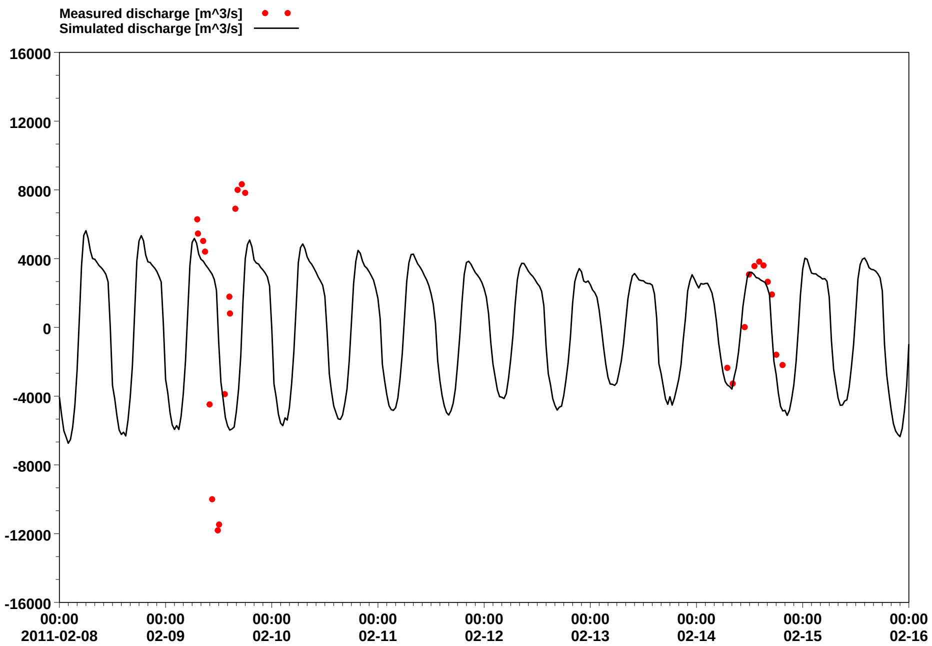

Figure 4.4 Discharge validation at Mongla Port during the dry season (February 2011)

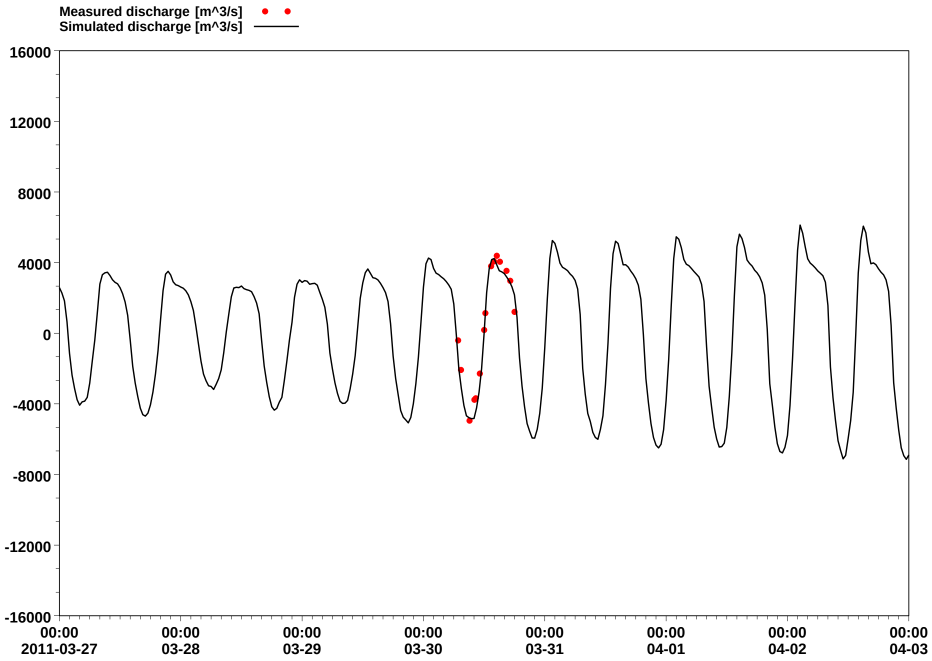

Figure 4.5 Discharge validation at Mongla Port during the dry season (March 2011)

Figure 4.6 to Figure 4.8 show the discharge calibration and validation at Akram Point in the Pussur river during monsoon and dry season. The computed discharge is well aligned with the measurement.

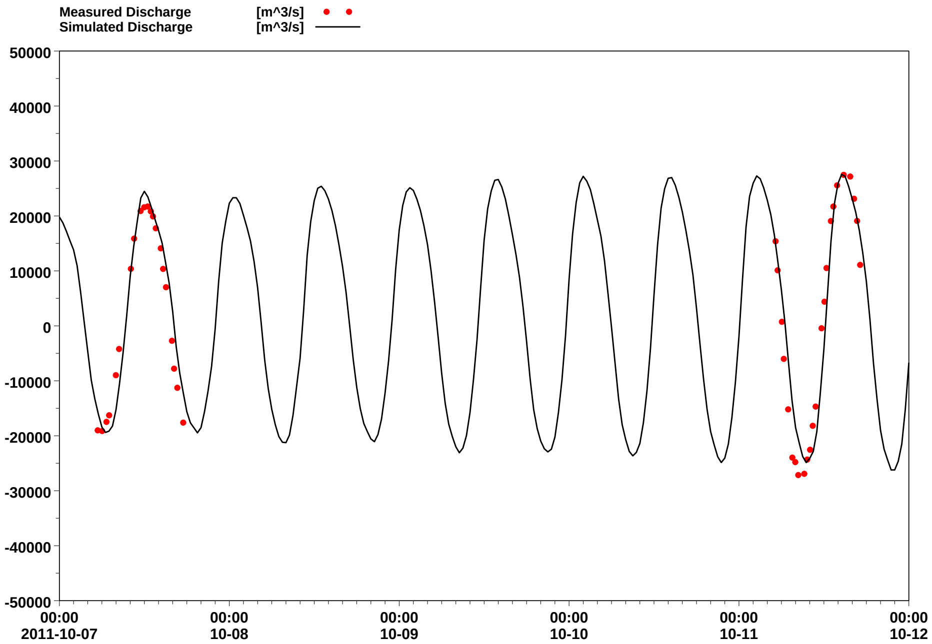

Figure 4.6 Discharge calibration at Akram Point in Pussur river during monsoon

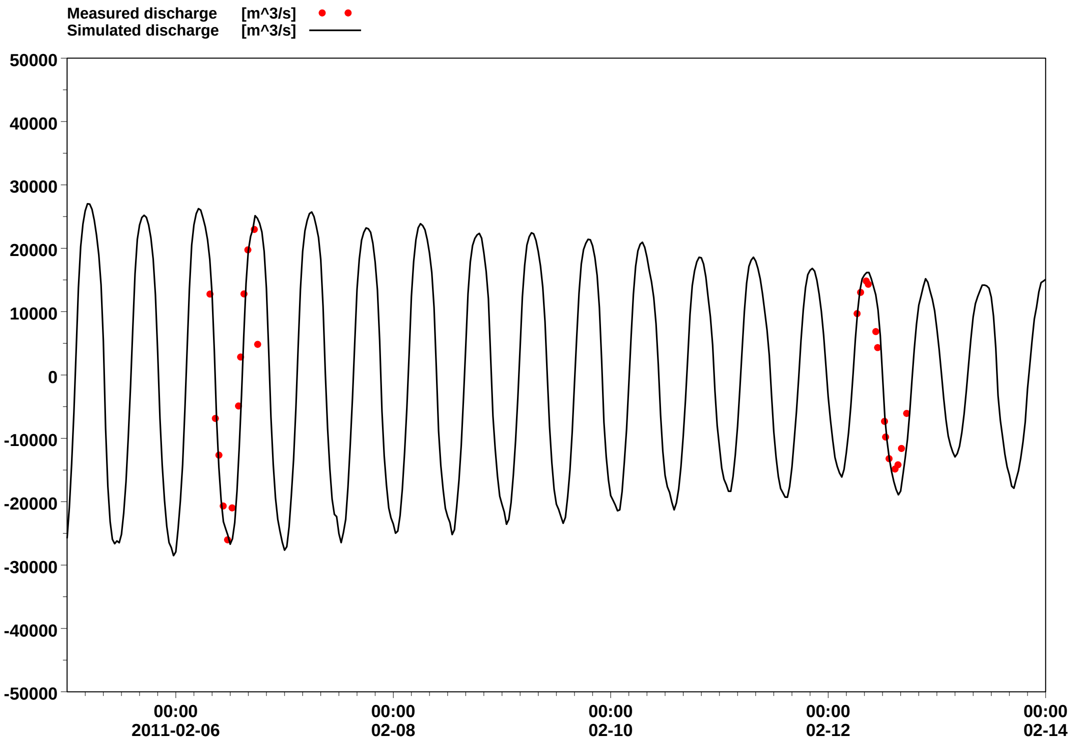

Figure 4.7 Discharge validation at Akram Point in Pussur river during the dry season (February 2011)

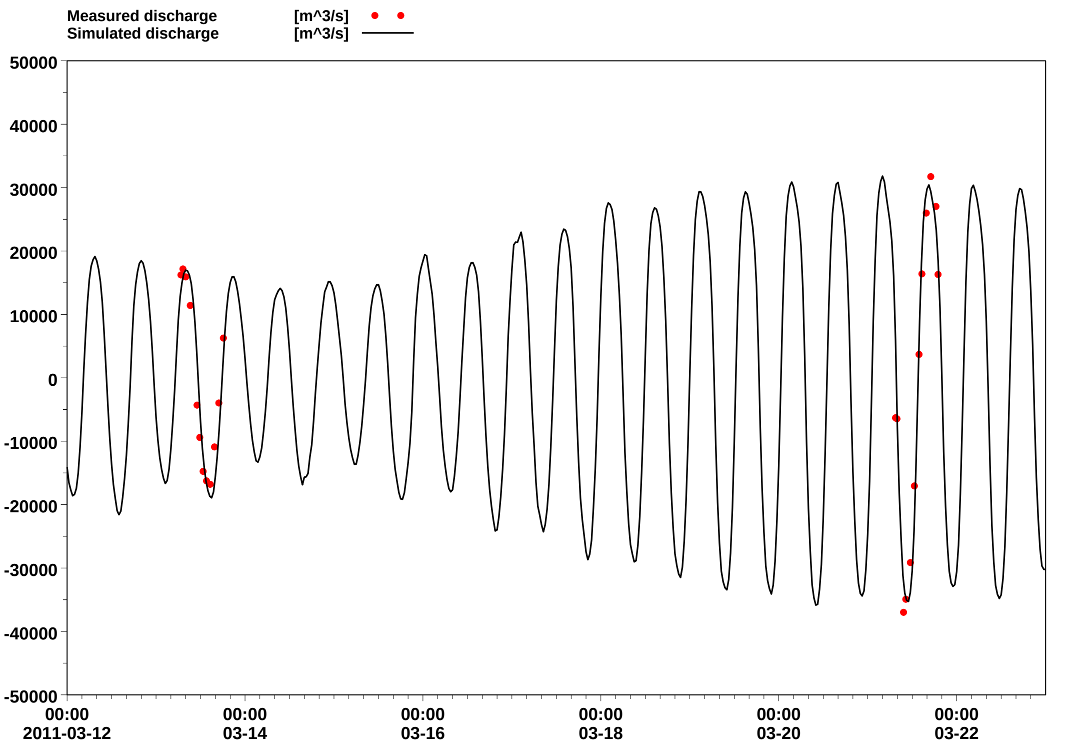

Figure 4.8 Discharge validation at Akram Point in Pussur river during the dry season (March 2011)

Figure 4.9 and Figure 4.10 show the discharge calibration and validation at Akram Point in Sibsa river during 2011 monsoon and dry season. The computed discharge is a little underpredicted especially during ebb flow. This may be due to upstream boundary condition from South West Regional Model. Another reason is the lack of tidal prism in the flood plain which could have retained more water volume during the flood flow. Again, as the error is within reasonable bounds, this is not considered a major shortcoming in the model.

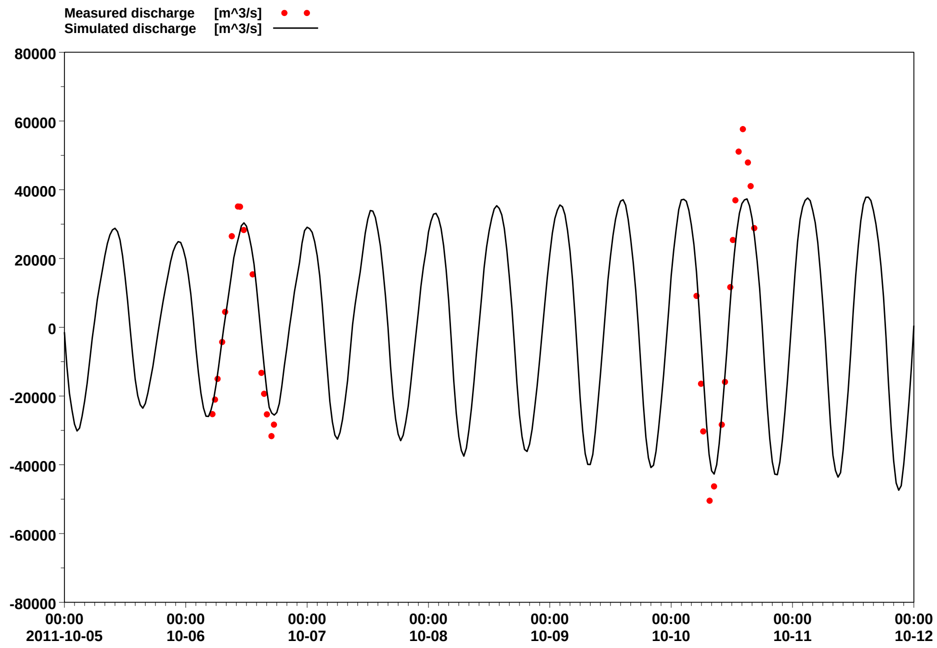

Figure 4.9 Discharge calibration at Akram Point in Sibsa river during monsoon (October 2011)

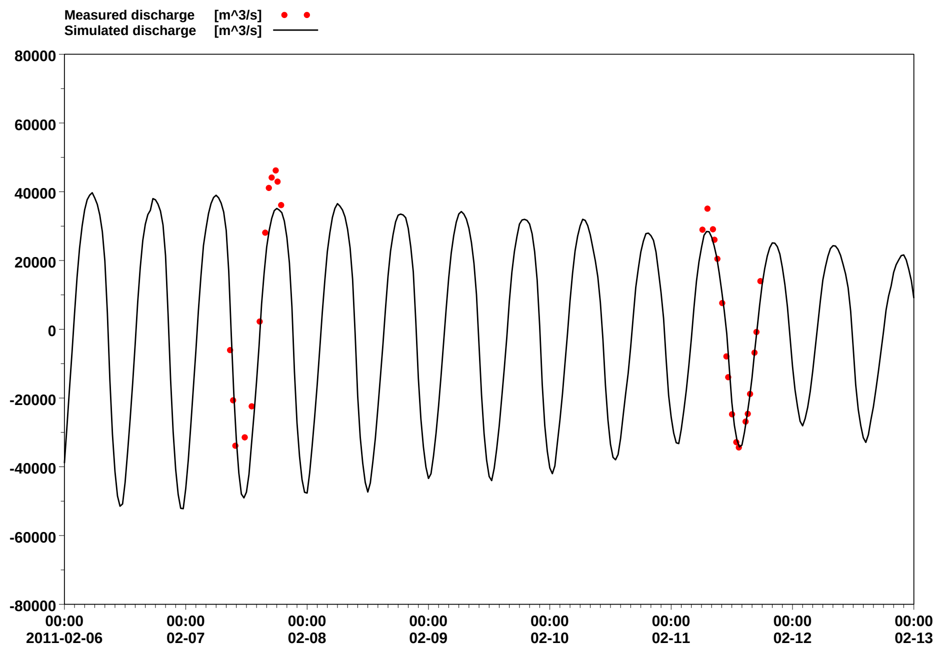

Figure 4.10 Discharge validation at Akram Point in Sibsa river during the dry season (February 2011)

4.4.2 Validation for water levels from 2011 during monsoon and dry season

The water level calibration and validation plots at Mongla Port are shown in Figure 4.11 and Figure 4.12 for the 2011 monsoon and dry season respectively. The computed water level underpredict levels especially during flood tide, but for ebb tide, the water level matches quite well. This follows the patterns in the discharge, which we have discussed in section 4.4.1.

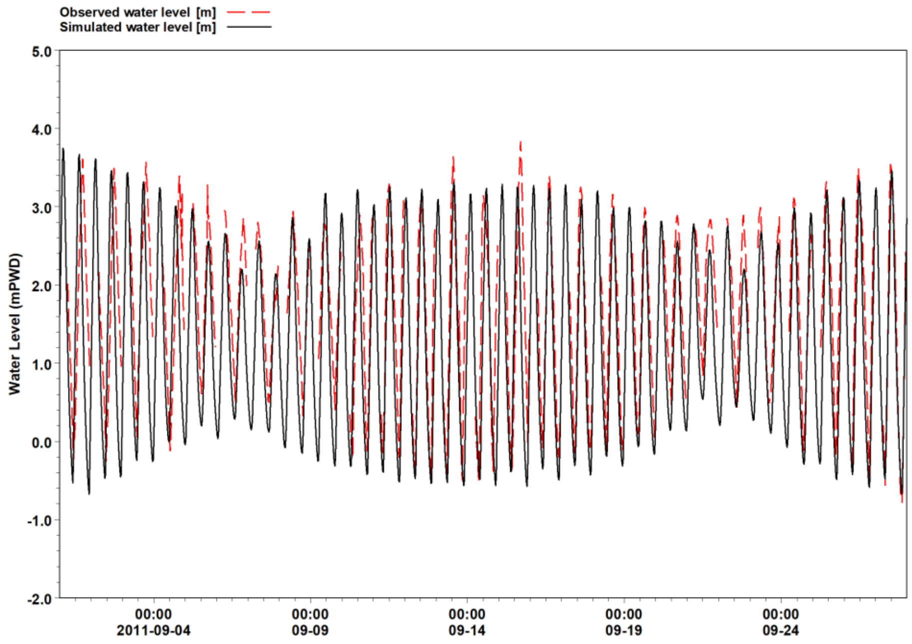

Figure 4.11 Comparison between observed and computed water level at Mongla Port during Monsoon (September 2011)

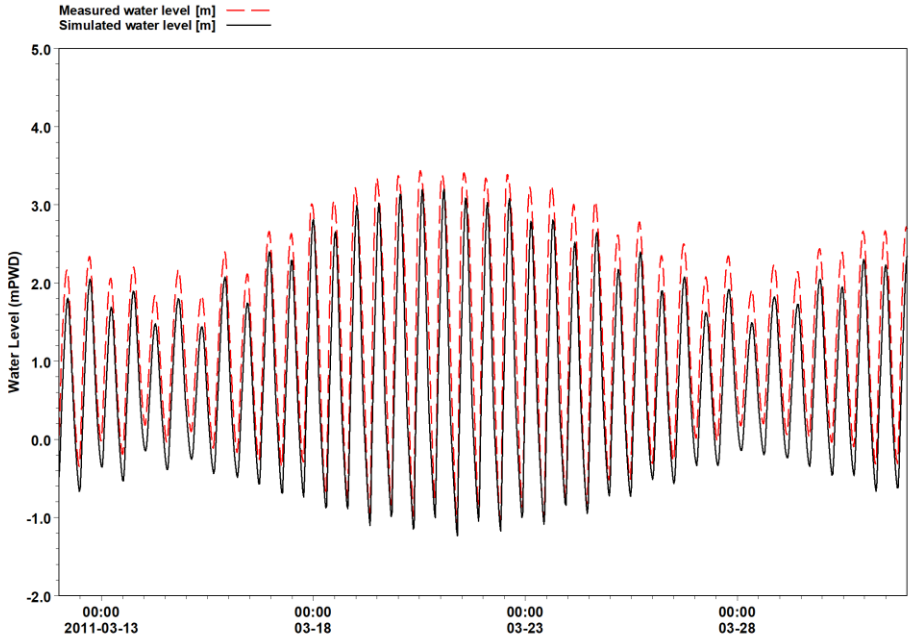

Figure 4.12 Comparison between observed and computed water level at Mongla Port during the dry season (March 2011)

4.5 Sediment model

The morphological model development for the Sibsa-Pussur river system was carried out for the year 2011. The Pussur-Sibsa river is cohesive in nature whereas some bed samples in the middle of the channel show non-cohesive sediment. Therefore, two sediment fractions were included: Sand and Mud. The detailed parameters used for the sediment model are illustrated in Table 4.9.

Table 4.9 Sediment model parameters for sand and mud fraction

[Sediment] Fraction 1 (Sand)		
Name	#sand#	Name
SedTyp	sand	Must be "sand", "mud" or "bedload"
IniSedThick	5	[m]
FacDss	1	Factor
RhoSol	2650	[kg/m³]
TraFrm	-1	Integer
CDryB	1600	[kg/m³]
SedDia	7.00E-05	[m]
IopSus	0	Option
AksFac	1	Calibration factor
Rwave	2	Calibration factor
RDC	0.01	[m]
RDW	0.02	[m]
IopKCW	1	Option for ks and kw
EpsPar	FALSE	Use Van Rijn's parabolic mixing coefficient
[Sediment] Fraction 2 (Mud)		
Name	#mud#	Name
SedTyp	mud	Must be "sand", "mud" or "bedload"
IniSedThick	5	[m]
FacDss	1	Factor
RhoSol	2650	[kg/m³]
TraFrm	-3	Integer
CDryB	500	[kg/m³]
SalMax	31	[ppt]
WS0	0.001	[m/s]
WSM	0.001	[m/s]
EroPar	0.001	[kg/m²s]
TcrSed	1000	[N/m²]
TcrEro	0.35	[N/m²]

4.6 Sediment transport boundary conditions

The first attempts to modelling were generated using constant boundary conditions with combined sand and mud concentrations as shown in Table 4.10. The side channel boundaries were set to zero (no sediment input). However, the definition of the boundary conditions will be improved by applying information from the 1D macro scale model, which will provide a more realistic boundary condition for this model. At present, that model has not been completed. Results should become available in the next quarter, and boundary conditions for the meso-scale model will be adjusted accordingly during the next phase of the calibration.

Table 4.10 Sediment concentration boundaries for the morphological model

Boundary	Sand (kg/m^3)	Mud (kg/m^3)
Sibsa (u/s)	0.40	0.45
Pussur (u/s)	0.40	0.45
Heron Point (d/s)	0.50	0.20

4.7 Sediment transport calibration

The application of the fluff layer concept improved model skill compared to runs without fluff layer, to the extent that suspended sediment concentration (SSC) levels are within the same order of magnitude. As in the 1D model the observed SSC is presented here as cross-sectionally averaged values. The modelled base SSC levels are similar to observed values (Figure 4.13). Fine tuning the fluff layer model could probably increase model skill.

The bed sediment model applies a fluff layer concept for the cohesive sediment modelling (Van Kessel et al., 2011). This implies that the bed consists of a lower layer with high critical shear stress and a thin upper layer that is more easily eroded, the so-called fluff layer. Exchange is possible between the lower and upper layer. The model thus assumes that the upper layer of the bed consists of easily erodible material with a low critical shear stress. Table 4.11 shows the fluff layer parameters that were used for the calibration.

Table 4.11 Sediment model parameters for sand and mud fraction with fluff layer (green shaded rows in fraction 2 are the fluff layer parameter)

[Sediment] Fraction 1 (Sand)		
Name	#sand#	Name
SedTyp	sand	Must be "sand", "mud" or "bedload"
IniSedThick	5	[m]
FacDss	1	Factor
RhoSol	2650	[kg/m³]
TraFrm	-1	Integer
CDryB	1600	[kg/m³]
SedDia	7.00E-05	[m]
IopSus	0	Option
AksFac	1	Calibration factor
Rwave	2	Calibration factor
RDC	0.01	[m]
RDW	0.02	[m]
IopKCW	1	Option for ks and kw
EpsPar	FALSE	Use Van Rijn's parabolic mixing coefficient
[Sediment] Fraction 2 (Mud)		
Name	#mud#	Name
SedTyp	mud	Must be "sand", "mud" or "bedload"
IniSedThick	5	[m]
FacDss	1	Factor
RhoSol	2650	[kg/m³]
TraFrm	-3	Integer
CDryB	500	[kg/m³]
SalMax	31	[ppt]
WS0	0.001	[m/s]
WSM	0.001	[m/s]
EroPar	0.001	[kg/m²s]
TcrSed	1000	[N/m²]
TcrEro	0.35	[N/m²]
DepEff	2.00E-01	[-]
ParFluff0	1.00E-04	[kg/m2/s]
ParFluff1	1.00E-05	[1/s]
TCrFluff	0.085	[N/m2]
IniFluffMass	0	[kg/m2]

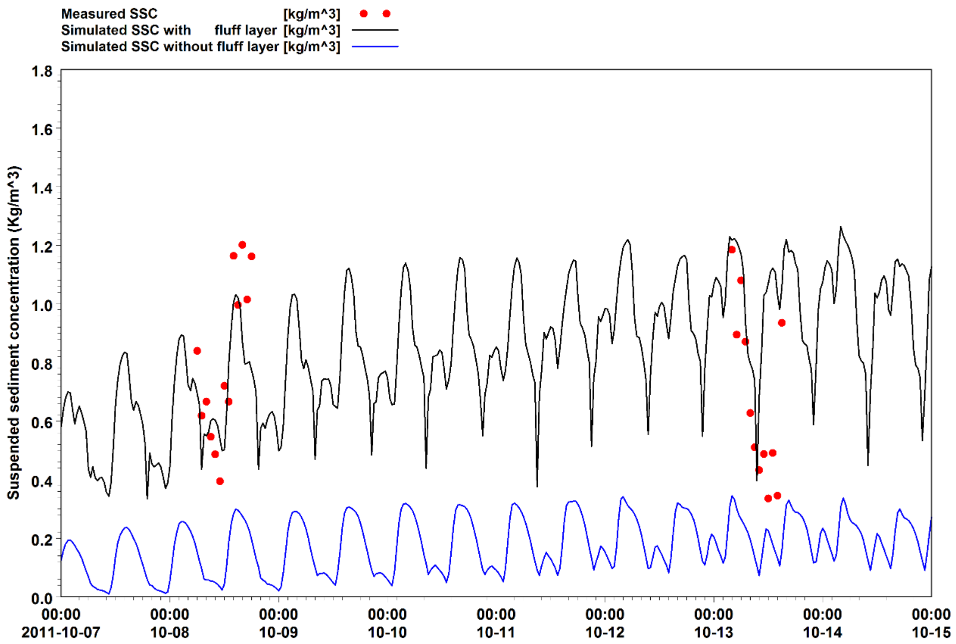

Figure 4.13 Comparison of modelled (with and without fluff layer) and observed Suspended Sediment Concentration at Mongla during monsoon (October 2011)

4.8 Morphodynamic model

4.8.1 Method

This section describes the calibration of the morphodynamic Pussur-Sibsa model against erosion and sedimentation patterns derived from measured bathymetries. The most complete data set available for such a comparison consists of bathymetric surveys around 2011 and 2019, i.e. an 8-year period.

The computational time for simulating a single year of hydrodynamics and morphology with a model such as this is in the order of 12-24 hours on a heavy computational cluster. Therefore, 'brute-force' simulations of the morphological evolution over decades would be extremely cumbersome. We applied the well-established approach of 'morphological acceleration' or MorFac method (Roelvink 2006, Ranasinghe et al, 2011) to make morphodynamic runs more efficient. This works as follows: in Delft3D the model solves hydrodynamics, sediment transport and bottom updating at every timestep; however, the morphological changes are multiplied by the MorFac (the Morphological Acceleration Factor), effectively accelerating the morphological evolution. Thus, after one tidal cycle, the effect on the morphology is as if a number of cycles equal to MorFac had been run. This approach is acceptable as long as the changes within one tidal cycle, even accelerated, are small relative to the water depth.

The tidal cycle can be left unchanged or can be schematized to a single representative tide. However, the yearly discharge curve has a much longer timescale and has therefore to be treated in a different way. As long as the discharge curve changes slowly, the flow distribution can be considered quasi-stationary. The hydrograph can then be accelerated, or 'squeezed' into a shorter time period, by the same MorFac. Squeezing the yearly hydrograph into two weeks does not fundamentally alter the flow distribution; after these two weeks all flow and transport events of a year have passed by. If now a MorFac of 26 (52 weeks divided by 2) is applied, then after one two-week cycle the morphological evolution of one year will have been simulated at the correct (morphological) speed. One hydrodynamic year with 26 such cycles is thus equivalent to 26 years of morphological change.

With a morphological factor of 26 it took approximately 112 hydrodynamic days (8 14-day hydrographs) to mimic a morphodynamic period of 8 years needed for the validation against the measured bathymetries. The model run time at the Deltares server was about 9 hours.

4.8.2 Hydrodynamic boundary conditions

The yearly hydrographs representing the landward river discharge boundaries of the Pussur and Sibsa rivers are squeezed into a 113/8=~14-day period. These boundary conditions were derived from the macro-scale model. Tidal discharge variations at the Sibsa boundary are about twice the variations at the Pussur boundary because the Pussur boundary is located more upstream and the Pussur estuary generally has a smaller cross-section. The cumulative discharge (river flow) at the Pussur boundary exceeds the discharge at the Sibsa boundary by a factor of ~3 (Figure 4.14). The water level at the seaward boundary is derived from the macro model under M2 tidal forcing and includes the seasonally varying water level setup due to monsoon winds (Figure 4.14) again squeezed into 14 days.

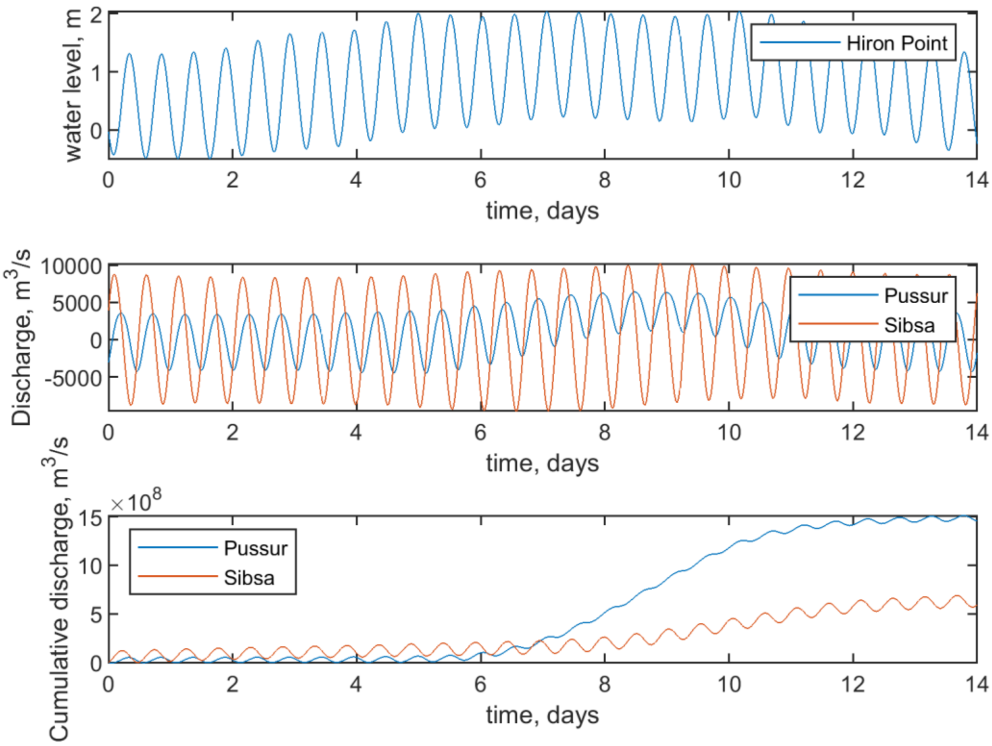

Figure 4.14 Seaward water level boundary (upper panel), discharge at Pussur and Sibsa boundaries (middle panel) and cumulative discharge at Pussur and Sibsa boundaries (lower panel)

4.8.3 Model settings

The sediment settings for the morphodynamic run are based on the settings applied in the macroscale model and differ from the settings applied in the SSC calibration described in previous sections of this report. The reason is that the macroscale model has advanced more and was already successfully calibrated against observed morphodynamic developments. Still, the Pussur-Sibsa meso-scale model needed specific adaptation of model parameters to optimise validation results.

The boundary conditions were derived from a fixed-bed, large-scale model run, since deriving them from a morphodynamic model run lead to instabilities. The bathymetry in the first 5 km from the seaward boundary had to be fixed (concrete bed) since including full morphodynamics in this area lead to excessive sediment concentrations, severe channel incision and unrealistic deposition patterns. Table 4.11 shows the model parameter settings of the standard run, i.e. the run that performed best.

We used sediment characteristics and sediment concentrations prescribed at the boundaries as calibration parameters and carried out limited sensitivity analysis on these parameters. This included varying the Pussur and Sibsa SSC boundary conditions to 750 mg/l and 250 mg/l, sediment availability in the bed (low, equal and high mud fraction compared to sand fraction) and a lower critical erosion shear stress (0.25-0.35 Pa) and varying the erosion parameter values (0.001, 0.0001 and 0.00001). Not all runs appeared to be stable.

Table 4.12 Pussur-Sibsa model parameter settings deviating from macro-scale model settings

Parameter	
Sand diameter	250 µm
Mud critical stress for erosion	0.3 N/m²
Mud erosion parameter	0.0001 kg/m²s
Mud fall velocity	0.5 mm/s
Dry bed density	850 kg/m³
Initial Sediment availability	No sediment available near sea boundary
Wetslope	No wetslope effect
Bed slope parameter	100
Mud SSC at Sibsa boundary	250 mg/l
Mud SSC at Pussur boundary	750 mg/l
Mud SSC at seward boundary	20 mg/l

4.8.4 Morphodynamic model results

The morphodynamic model simulated the period from 2011 to 2019. The presented model results reflect the best run from a series of sensitivity runs varying the sediment parameters and hydraulic forcing conditions. Figure 4.15 shows the observed and modelled erosion/deposition maps.

Measured and modelled erosion and deposition heights are in the same order of magnitude. The modelled amount of sediment in the Pussur remains less than observed amounts. Modelled deposition in the Pussur concentrates more towards the landward boundary. Generally, erosion and sedimentation patterns are reproduced better near sharp bends and in the Sibsa compared to the Pussur.

Over the 9 years of modelling time, the bed composition in the first 10-20km from the boundaries becomes muddier, channels generally become more sandy while mud deposits on the shoals and shallower areas near the banks. These trends correspond with the limited observations available shown in Table 3.5 and Figure 3.4.

The standard run shows channel incision in the Pussur (middle panel Figure 4.15). This could be prevented by decreasing the initial mud fraction available in the bed from 50% to 20% (left panel Figure 4.15). This latter run performed slightly worse though in volume reproduction.

The Pussur-Sibsa area is subdivided into sub-areas to make a closer volume analysis possible, see Figure 4.16. Figure 4.17 shows that the erosion and deposition volumes and the net volume change develop gradually, most of them with an absolute-value increasing trend. In most areas, the trend is larger during the first-years suggesting a morphodynamic spin-up and/or a realistic decline of morphodynamic activity due natural development towards equilibrium. The hypsometries of areas 1,2,3,4 and 7 remain similar, but areas 5 and 6 show significant adaptation. The change measured hypsometries remains limited, which is well reproduced by the model except for areas 5 and 6. The shape of the modelled hypsometry of area 7 resembles the observed hypsometry albeit that the final level is higher than the observed hypsometry.

Finally, Figure 4.18 and Table 4.13 summarize the model performance by comparing observed and modelled volumes leading to an overall correlation of 0.86. Figure 4.18 and Table 4.14 show that correlation coefficients of different sensitivity runs are close and may even be better for erosion or deposition volumes.

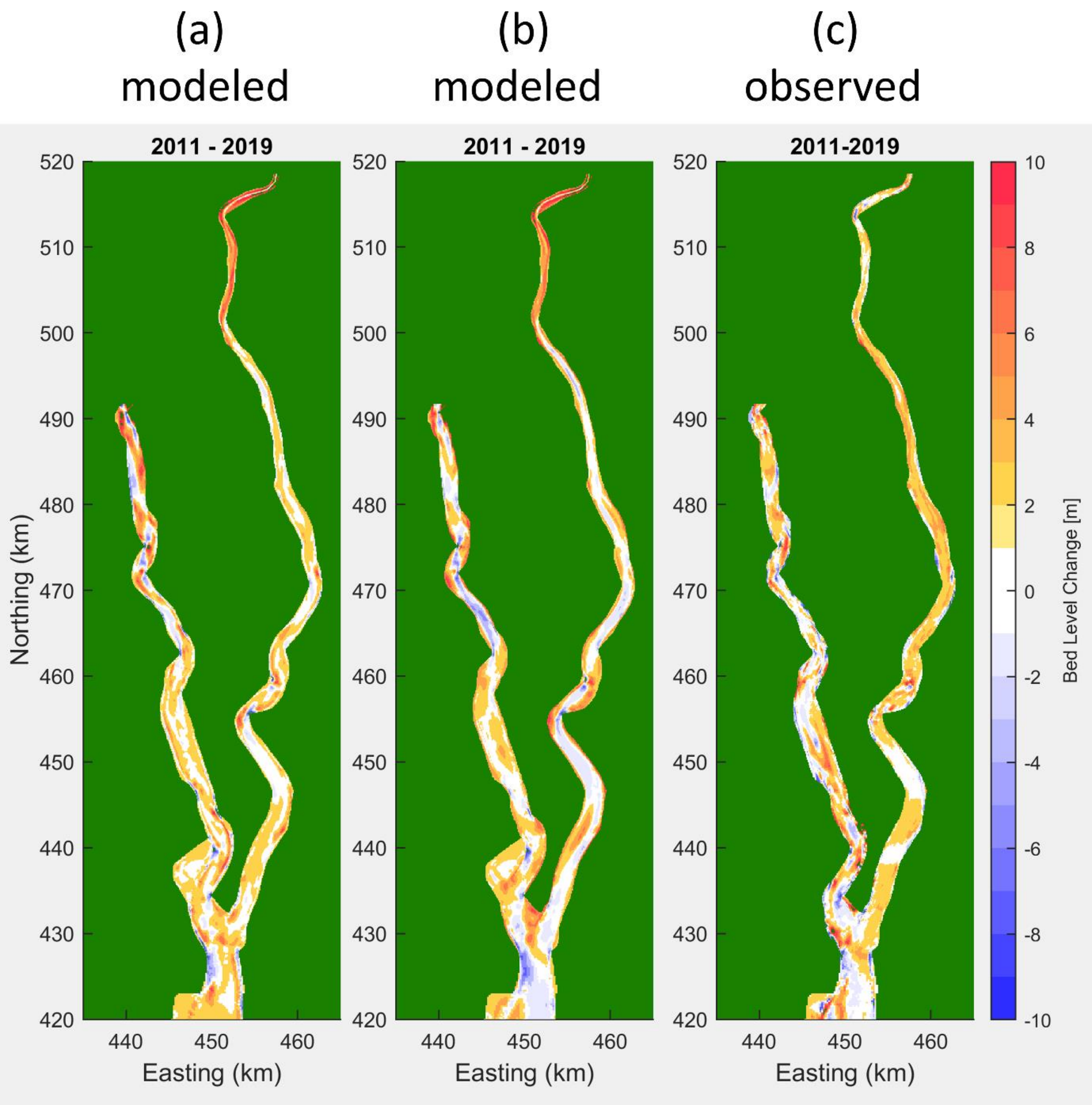

Figure 4.15 Sedimentation/erosion pattern after 8 years (2011 to 2019), measured (left and middle panel) and modelled (right panel). The middle panel is the standard run with settings depicted in Table 4.11. The left panel shows results with 20% mud fraction in the initial bed instead of 50%.

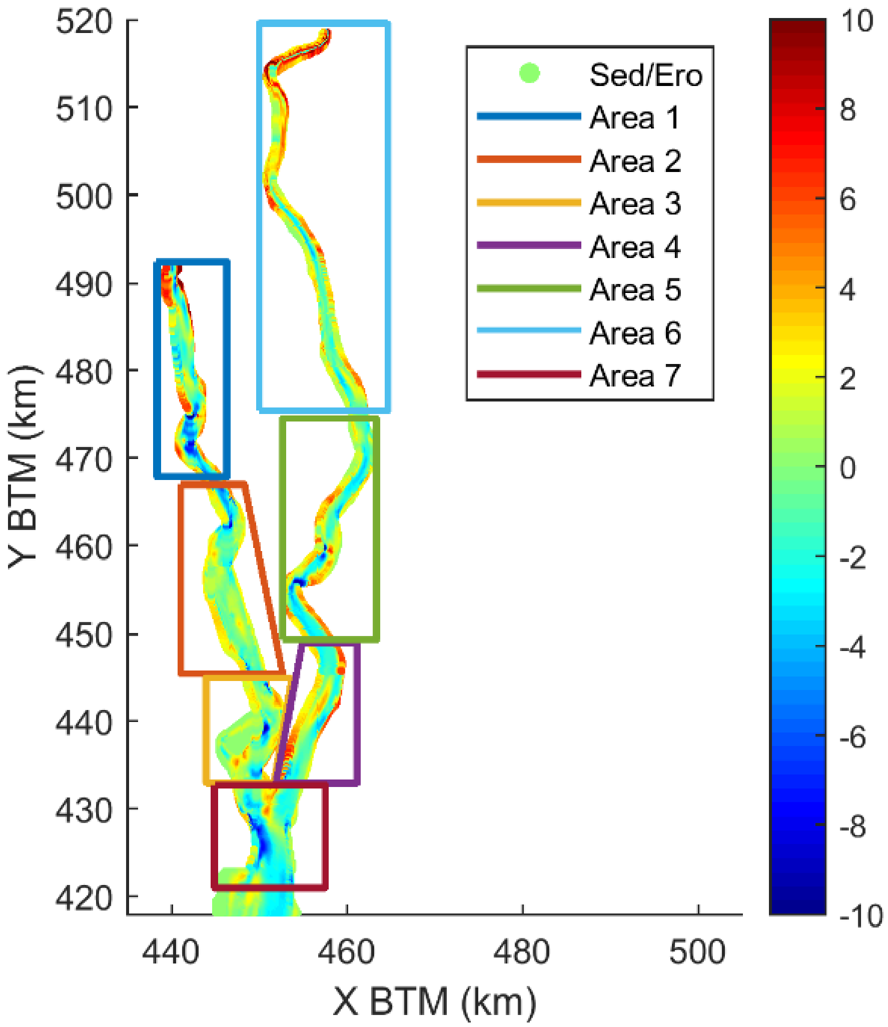

Figure 4.16 Area definition on modelled 2011-2019 erosion and sedimentation patterns in m

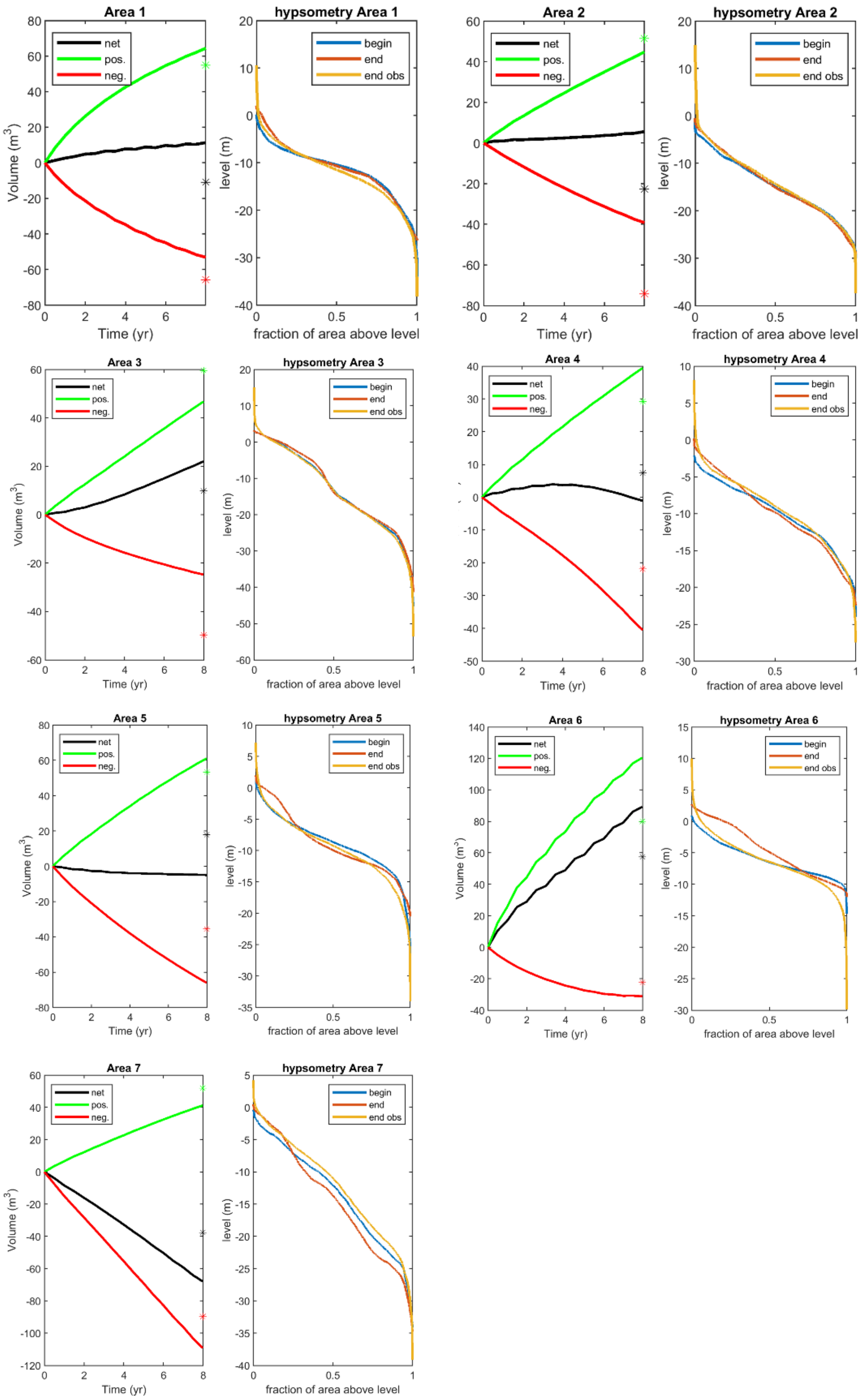

Figure 4.17 Cumulative modelled erosion volumes, deposition volumes and area-net volumes (left panels) and hypsometries at the start (2011) and end (2019, modelled) (right panels) for different areas as defined in Figure 4.16. Observed volumes are indicated by (*)

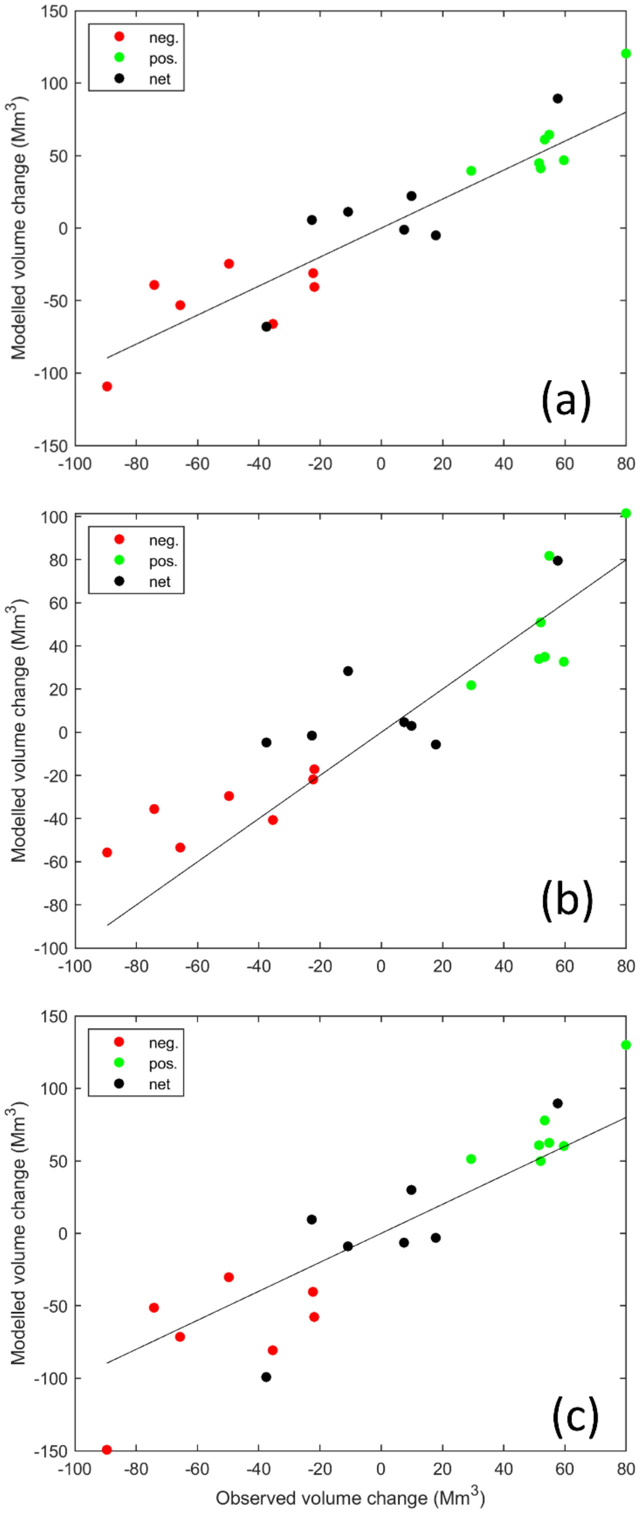

Figure 4.18 Comparison of observed and modelled erosion volumes, deposition volumes and area-net volumes of all areas as defined in Figure 4.16. (a) Standard run, (b) run with limited mud availability in initial bed (20% compared to 50%) and (c) run with limited mud availability in initial bed and low critical erosion shear stress ($\tau_{cr,e}$=0.2 Pa)

Table 4.13 Standard run performance for erosion volume, sedimentation volume and net volume compared to observations as shown in Figure 4.17 and Figure 4.18. RMSE denotes root mean square error, MAE denotes mean average error, SLOPE indicates the slope of trendlines in Figure 4.18 (1 implies a perfect fit) and CORR denotes the correlation coefficient.

Parameter	Erosion	Deposition	Net
RMSE	25 Mm^3	18 Mm^3	25 Mm^3
BIAS	-1 Mm^3	5 Mm^3	5 Mm^3
MAE	21 Mm^3	14 Mm^3	22 Mm^3
SLOPE	1.01	1.10	2.50
CORR	0.59	0.82	0.86

Table 4.14 Correlation coefficient values for different model runs

Parameter	CORR Erosion	CORR Deposition	CORR Net
standard	0.59	0.82	0.86
Limited mud availability	0.81	0.76	0.72
Limited mud availability and low $\tau_{cr,e}$	0.60	0.81	0.85

4.8.5 Discussion

The morphodynamic model performs quite well compared to similar other international case studies, especially given the lack of data for boundary condition definition and model calibration and validation (e.g. Dam et al. 2016, Elmilady et al. 2019). Model performance may be increased by including side branches in the Pussur-Sibsa system, dredging operations and wave action and further sensitivity analysis on model parameters.

The objective of the current study was to understand the major morphological changes including the main driving processes in current day circumstances. Our modelling effort shows that realistic morphodynamic patterns can be achieved under schematized, average forcing conditions, 2D flow and rough, but best estimate sediment characteristics. This suggests that major morphodynamic developments arise from the interaction between dominant forcing conditions (i.e. regular tidal movement, representative river flow and sediment supply) and the estuaries' plan form. Yearly variations of the schematized forcing conditions will probably have a limited impact, especially when long, decadal time scales are considered.

Model performance can be improved by adding complexity in process descriptions like 3D flow, salt-fresh water interaction, multiple sediment fractions, but improvement will likely be of second order. Also, in that case, much more data would be required to validate if the added complexity is justified.

A major challenge was the definition of the boundary conditions, both at sea and at the landward side. Hydrodynamic observations at these locations do not exist and had to be derived from the macroscale model. Also, sediment concentration levels are not known and had to be estimated. This introduced uncertainties and significant instabilities in the model, which had to be overcome by imposing a non-erodible bed near the seaward boundary.

The boundaries were chosen such that they covered the measured bathymetries extent needed for assessing the model performance. One may question if these were the right locations given the fact that the landward boundaries are under significant tidal influence. The determination of the sediment concentration levels at the boundary appeared to be a challenge. They had significant influence on the model results and also often led to model instabilities. On the other hand, a boundary located more upstream would have raised similar questions on the sediment concentration levels and extra questions on the presence and validity of the bathymetry.

A possible solution to this boundary location dilemma is the nesting of the high resolution, meso-scale models in the macro-scale model. Tidal propagation and sediment concentrations at the current boundaries would then be more continuous and in line within the (validated) large-scale model context. However, questions on model validation would still remain due to limited data availability.

5 Conclusions

This report aims at understanding and predicting the morphological behaviour of the Pussur-Sibsa river system on decadal scales and scenarios of climate change. A second objective is to provide smaller scale models with suitable boundary conditions of bed levels and suspended sediment concentrations for these scenarios.

We developed a Delft3D FM model based on an inventory of scarce data on bathymetries, bed sediment properties, water level observations and suspended sediment concentration (SSC) measurements. The Pussur-Sibsa model was successfully calibrated against measured water levels from 2011 and observed SCC, applying hydrodynamic boundary conditions derived from the macro-scale model at the seaward boundary and from the MIKE SM model at the landward boundaries.

We validated the morphodynamics of the Pussur-Sibsa model against erosion and deposition patterns for the 2011-2019 period. This validation was based on adjusted sediment properties derived from the more advanced and successfully morphodynamically calibrated macro-scale model. Adequate model boundary condition determination remains a challenge due to limited data availability however model results show significant resemblance to measured data.

Model results suggest that the major morphodynamic developments on the scale of channels and shoals arise from interaction between the estuaries' plan form and major forcing conditions such as tide and river flow and sediment characteristics such as grain size. Yearly variations in forcing conditions instead of the used schematised forcing conditions and more complex process -descriptions such as 3D flow may improve the model performance but are probably only important only at second order and would require much more validation data which is not available.

The model results can be improved by further sensitivity analysis exploring the impact of dredging operations, wave action, and including estuary side channels and secondary channels connecting the Pussur and Sibsa estuaries. Also, the model results appear to be sensitive to uncertain boundary conditions such as seaward and landward suspended sediment concentrations and river flow discharges.

6 References

Dam, G., Van der Wegen, M., Labeur, R. J., & Roelvink, D. (2016). Modeling centuries of estuarine morphodynamics in the Western Scheldt estuary. *Geophysical Research Letters*, *43*(8), 3839-3847.

Elmilady, H. M. S. M. A., Van der Wegen, M., Roelvink, D., & Jaffe, B. E. (2019). Intertidal area disappears under sea level rise: 250 years of morphodynamic modeling in San Pablo Bay, California. *Journal of Geophysical Research: Earth Surface*, *124*(1), 38-59.

Roelvink, J.A., 2006. Coastal morphodynamic evolution techniques. *Coastal engineering*, *53*(2-3), pp.277-287.