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)

MIKE 21C Sibsa meso-scale bank erosion morphological modelling study: Model development report

Joint Venture of DHI The expert in WATER ENVIRONMENTS & Deltares Enabling Delta Life in association with IWM, Bangladesh and University of Colorado, Boulder and Columbia University

October 2020

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)

MIKE 21C Sibsa meso-scale bank erosion morphological modelling study: Model development report

October 2020

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

University of Colorado, Boulder, USA
Columbia University, USA

CONTENTS

FIGURES

ACRONYMS AND ABBREVIATIONS

ADCP- Acoustic Doppler Current Profiler

BDP2100- Bangladesh Delta Plan 2100

BIWTA- Bangladesh Inland Water Transport Authority

BMD- Bangladesh Meteorological Department

BoB- Bay of Bengal

BWDB- Bangladesh Water Development Board

CBA- Coast Benefit Analysis

CCP- Chittagong Coastal Plain

CDMP-Comprehensive Disaster Management Program

CDSP- Char Development Settlement Project

CEA- Cost Effectiveness Analysis

CEGIS- Centre for Environmental and Geographic Information Services

CEIP- Coastal Embankment Improvement Project

CEP- Coastal Embankment Project

CERP-Coastal Embankment Rehabilitation Project

CPA- Chittagong Port Authority

CPP-Cyclone Protection Project

CSPS-Cyclone Shelter Preparatory Study

DDM- Department of Disaster Management

DEM- Digital Elevation Model

DOE- Department of Environment

EDP- Estuary Development Program

FAP- Flood Action Plan

FM- Flexible Mesh

GBM- Ganges Brahmaputra Meghna

GCM- General Circulation Model

GIS- Geographical Information System

GTPE- Ganges Tidal Plain East

GTPW- Ganges Tidal Plain West

HD- Hydrodynamic

InSAR- Interferometric Synthetic Aperture Radar

IPCC- Intergovernmental Panel for Climate Change

IPSWAM- Integrated Planning for Sustainable Water Management

IWM- Institute of Water Modelling

LCC- Life Cycle Costs

LGED- Local Government Engineering Department

LGI- local Government Institute

LRP- Land Reclamation Project

MCA- Multi Criteria Analysis

MES- Meghna Estuary Study

MoWR- Ministry of Water Resources

MPA- Mongla Port Authority

NAM - Nedbor Afstromnings Model

PPMM- Participatory Polder Management Model

PSD- Particle Size Distribution

RCP- Representative Concentration Pathways

RTK- Real-Time Kinematic

SET-MH- Surface Elevation Tables – Marker Horizons

SLR- Sea Level Rise

SOB- Survey of Bangladesh

SSC- Suspended Sediment Concentration

SWRM- South West Region Model

TBM- Temporary Bench Mark

TRM- Tidal River Management

ToR- Terms of Reference

WARPO- Water Resources Planning Organization

WL - Water Level

1 Introduction

The prediction of bank erosion hinges on the already complicated prediction of bathymetry in a river, with strong feedback between the planform and bathymetry. This makes bank erosion prediction complex, and to make things worse, the complexity is increased compared to the complexity associated with predicting the bathymetry development.

Nevertheless, we find encouragement when studying historical bank erosion development in the coastal zone from satellite imagery. Sometimes it can be awfully complicated to predict bank erosion more than a few years into the future due to degrees of freedom in a braided river such as Jamuna River for instance. In the tidal rivers investigated, however, channel morphology with bars and the associated planform looking the same since 1988 (they are interconnected) gives rise to optimism when it comes to predicting bank erosion.

The following meso-scale models were originally planned:

- 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)

Originally, the intention was to develop model groups, i.e. a Pussur-Sibsa model, but for bank erosion with moving grids it is better to develop separate models, i.e. one model for each river. The same applies to Baleswar and Bishkhali. The revised list of models, listed from west to east:

- Sibsa (Polder 32)
- Pussur (Polder 33)
- Baleswar (Polder 35/1, 39/1, 39/2, **40/1**, **40/2**)
- Bishkhali (Polder 39/1, 39/2, **40/1**, **40/2**, 41, 42)
- Lower Meghna (Polder 56/57 and **59/2**, no progress since March due to Covid-19)
- Sangu (Polder 63/1a, 63/1b, **64/1b**, currently under development by IWM)

Tentulia was removed from the list due to lack of resources. The models are very time-consuming to develop, and the original list was not realistic. Key polders in the list are shown in bold.

The report structure for the meso-scale bank erosion models is organised with two reports for each model:

- Model Development Report
- Model Application Report

The present report is the Model Development Report for the Sibsa River bank erosion model.

1.1 Concerning graphical presentation for Sibsa River

We use several figures showing results in ways that can seem confusing if the reader is not being made aware that:

- Some plots show several Sibsa River maps side-by-side
- Some plots show Sibsa River divided into upstream and downstream

The plots with several Sibsa River 2D maps shown next to each other are useful for showing several results together because they belong together. Examples include bathymetries that need to be compared. When showing these, the 2D maps are displaced 5 km in eastern direction (to the right), and the easting coordinates are hence only correct for the first 2D maps shown to the left in the group.

The divided maps are used because the Sibsa model is very long, so showing the river in a report will result in narrow figures. Instead the river is divided into upstream and downstream halves, which are shown next to each other.

For one-dimensional variations we utilize the fact that the Sibsa River runs almost north to south, so we can use the BTM northing coordinate and avoid having to introduce a separate longitudinal coordinate, such as chainage.

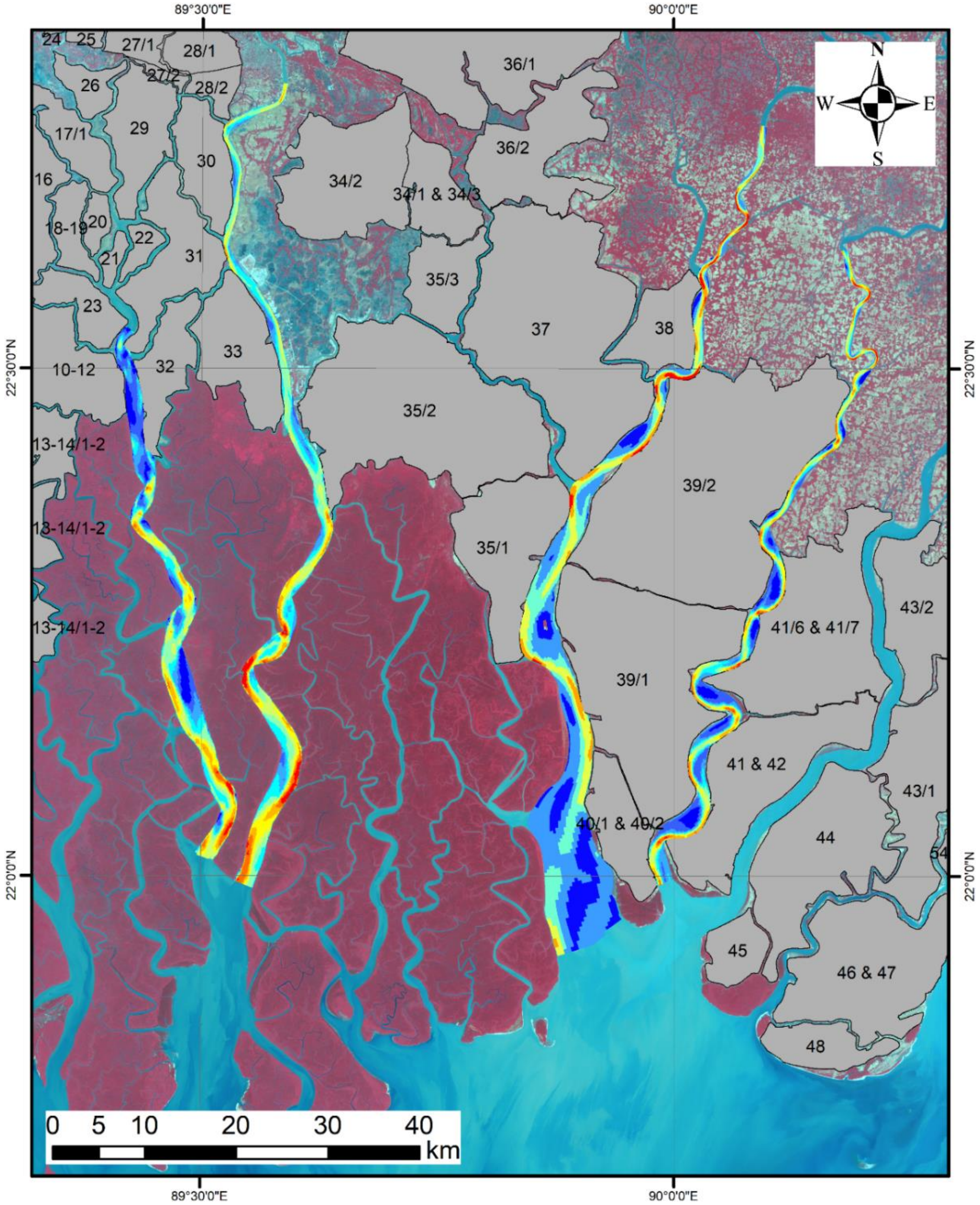


Figure 1-1 The four MIKE 21C models developed for the project.

2 Objectives and Approach

The main objective of this modelling is to develop a predictive bank erosion tool for the selected rivers around the polder area and to estimate future bank line changes under different scenarios.

The general approach for this modelling is the following:

- Preliminary study of historical bank erosion in the larger tidal rivers by using satellite imagery
- Digitization of historical bank lines (Landsat) for the selected rivers
- Review of publications related to bank erosion with the emphasis on identifying the most suited bank erosion description for the tidal rivers in Bangladesh
- Setup and calibration – set up, calibrate and validate the model with field measurements and remote sensing data
- Morphological hindcast – reproduce the bank line shifting from previous different periods
- Scenario runs - study future changes in the morphological processes based on possible scenarios
- Output - geospatial datasets of present erosion and sedimentation in the river system for various seasons and for possible scenarios 25, 50 and 100 years from now, for various seasons and circumstances.

3 Data

In this section we document all the data that was used for the model development.

The projection is BTM and the vertical datum is mPWD.

3.1 Bathymetry

Data collection has taken place on the river, i.e., data already exists. A very detailed bathymetry survey was conducted in 2011 for the Sibsa river system from the GRRP project. A similar bathymetry survey was conducted in 2019 for the present project.

Old bathymetry datasets exist, but none has the required resolution for 2D contouring.

Table 3-1 Bathymetry data for Sibsa River

Bathymetry data collection year	Sources
1977-92	SWMC
2001	IWM
2011	IWM (GRRP)
2019 (March)	Primary data (present project)

General information for the available bathymetry datasets is shown in Table 3-1.

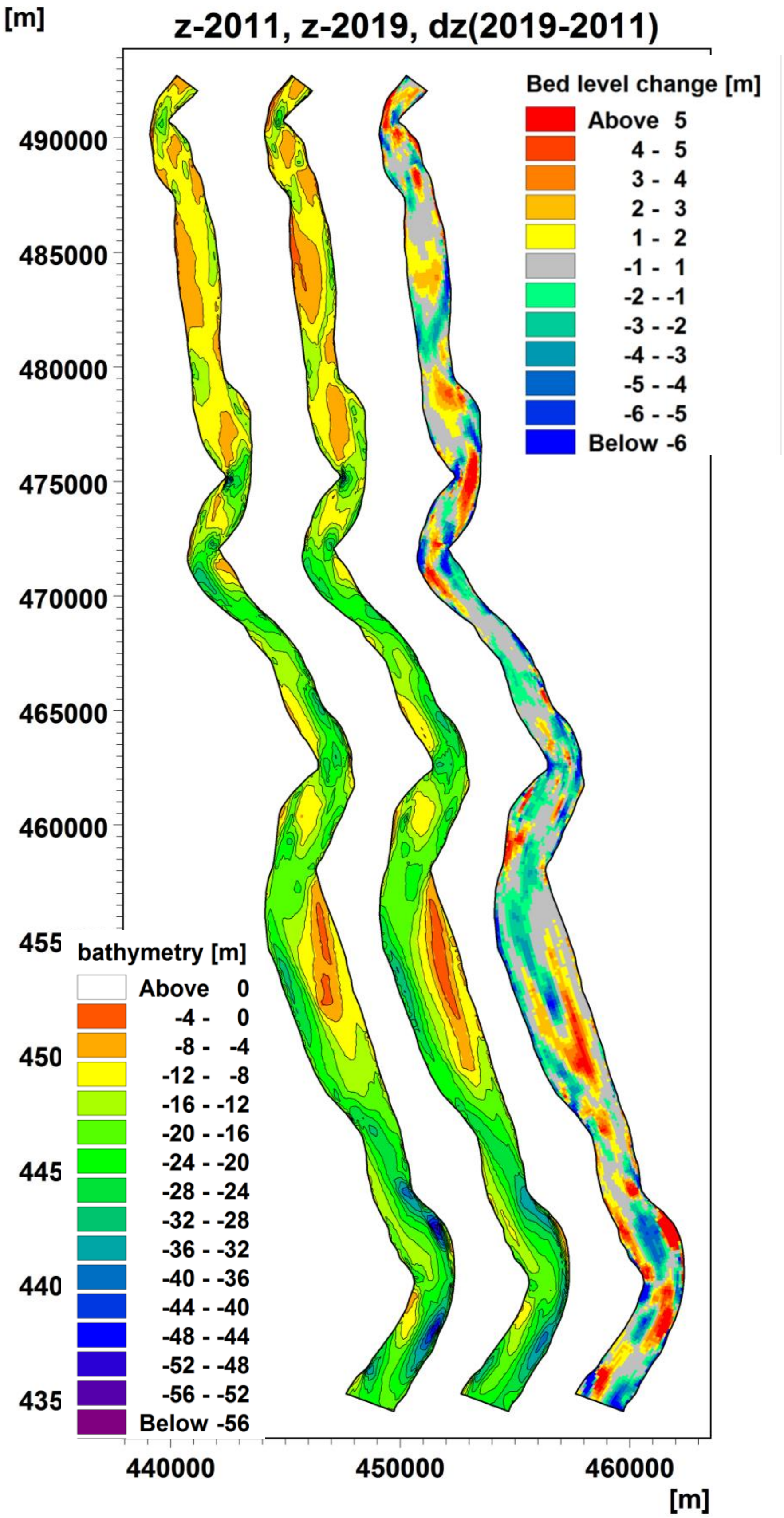


Figure 3-1 Bathymetry and bed level changes 2011-2019, from left: 1) 2011 bathymetry, 2) 2019 bathymetry, 3) bed level changes 2011-2019.

The bathymetries and associated changes 2011-2019 are shown in the Figure 3-1.

3.2 Hydrometric time-series

There are no water level measurements for 2011. Water level at Nalian was collected for 2015 by IWM under the CEIP-1 project. In the present study, water levels are collected at Nalian in the beginning of 2019.

Table 3-2 Available water level observations from Sibsa River

Water level collection year	Station name	Sources
2015	Nalian	CEIP-1 project
2019	Nalian	Primary data (present project)

Table 3-3 Available discharge observations from Sibsa River

Discharge collection year	Station name	Sources
2011	Akram Point	IWM (GRRP)
2016	Nalian	CEIP-1 project
2019	Nalian	Primary data (present project)

The stations are shown in Figure 3-2, while datasets details are provided in Table 3-2 and Table 3-3. The discharge data was collected by IWM, typically during one day using tide tables to plan for neap and spring data collection. Water levels were collected at the same time, and often IWM also collects suspended sediment concentration data with the ADCP data. Water level stations are often permanent and contain water levels collected every 30 min.

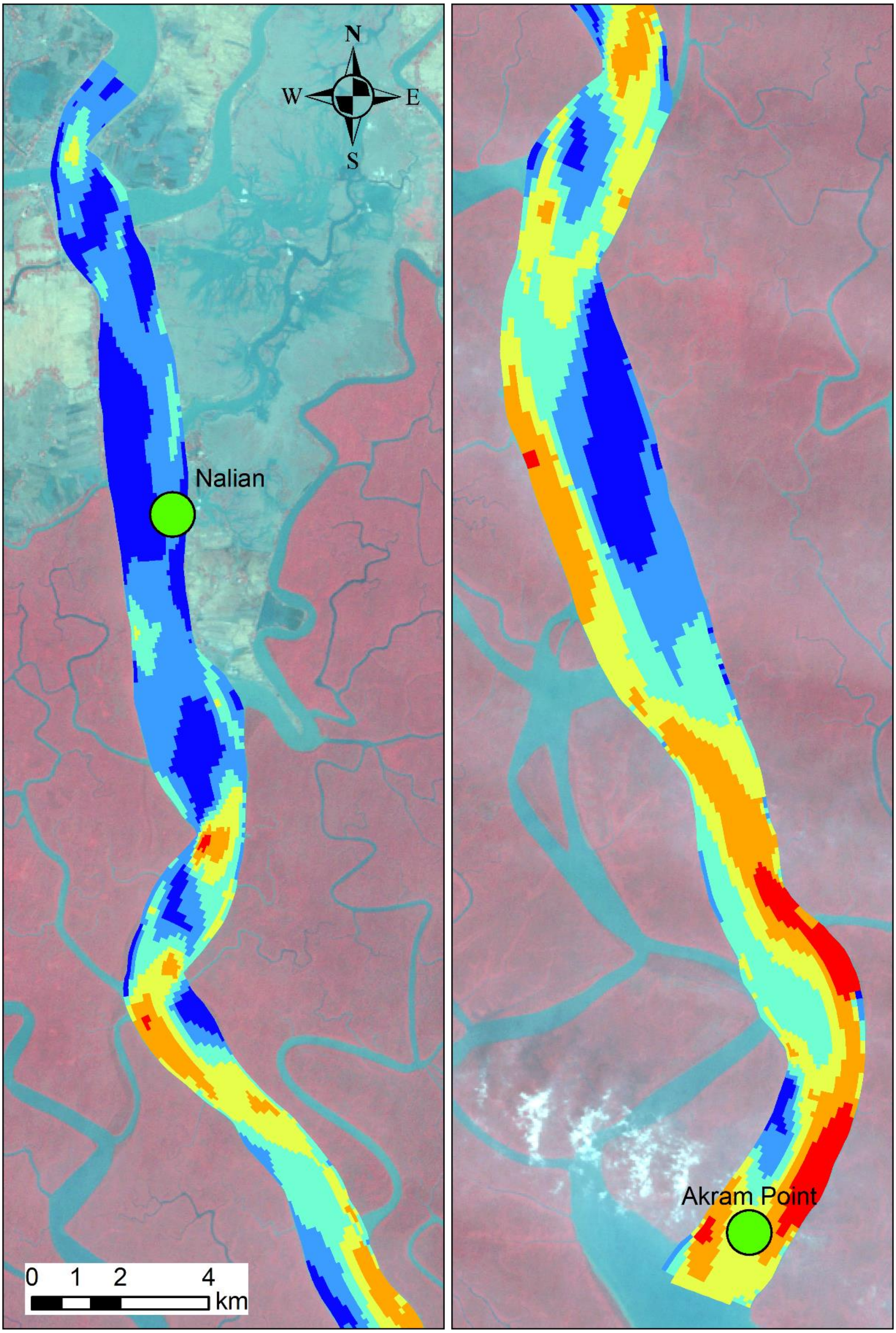


Figure 3-2 Field data collection map for 2011, 2015, 2016 and 2019.

3.3 Sediment bed samples

In this section we compile all readily available bed samples for the Sibsa River. Many samples have been collected for various projects, but we have not found any report that compiled the data to obtain a comprehensive picture of the sediment bed.

It is possible that old bed samples exist. It would be natural to expect that e.g. the original Pussur-Sibsa study involved bed samples.

Table 3-4 Available bed samples for Sibsa River.

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

Bed samples inventory is presented in Table 3-4.

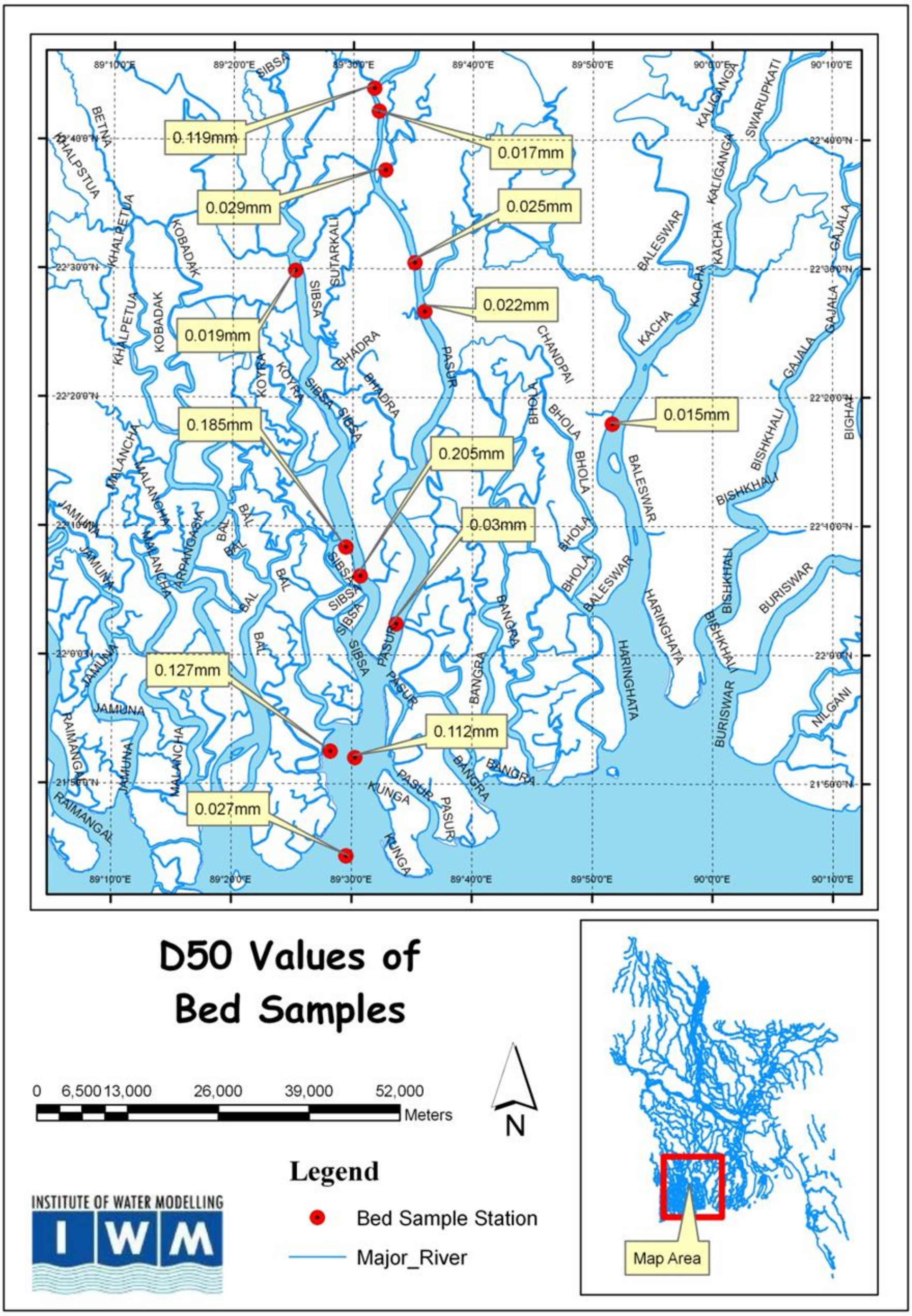


Figure 3-3 Bed samples d_{50} with locations during 2011 for the GRRP project.

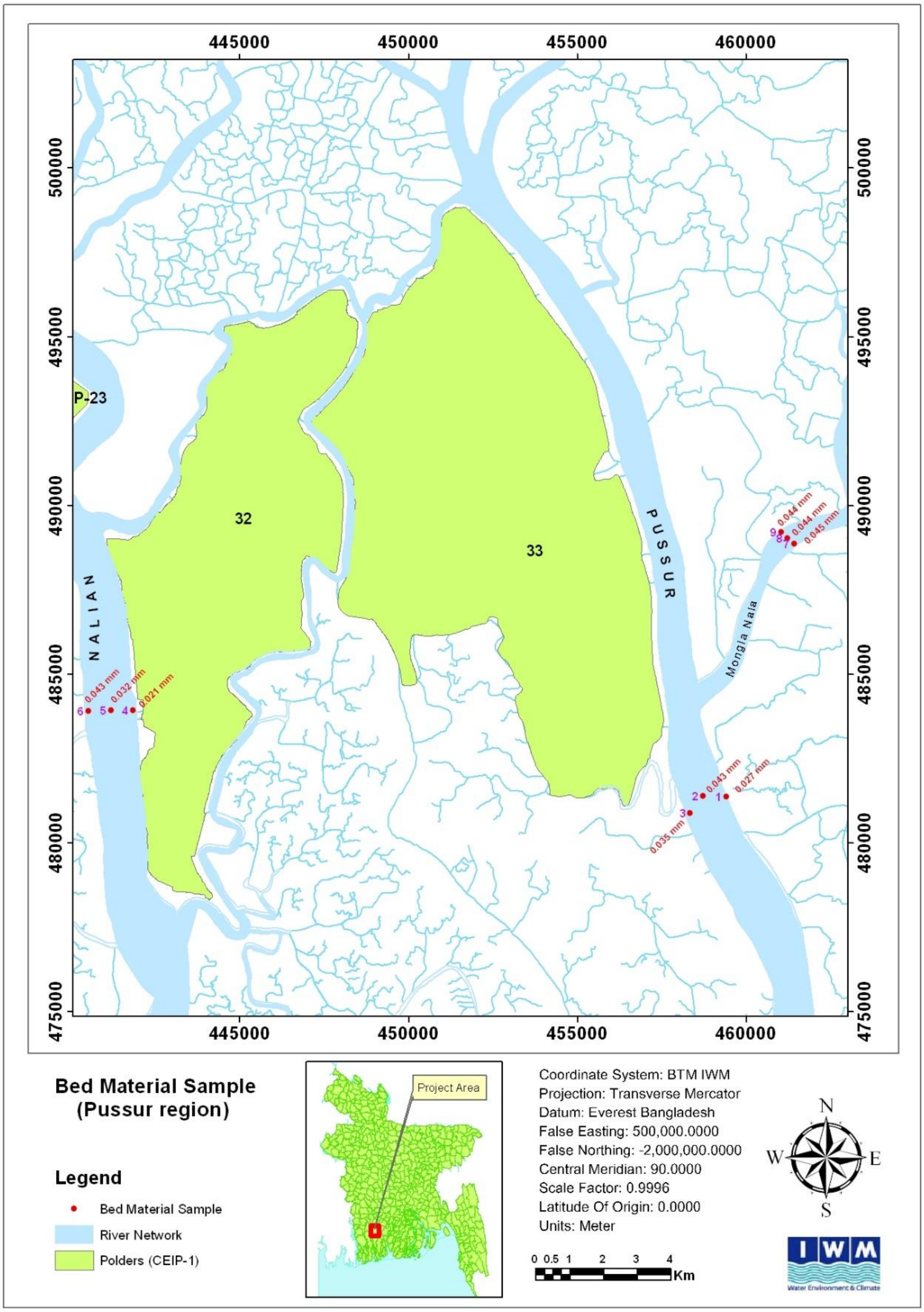


Figure 3-4 Bed samples d_{50} with locations during 2016 for the CEIP-1 project

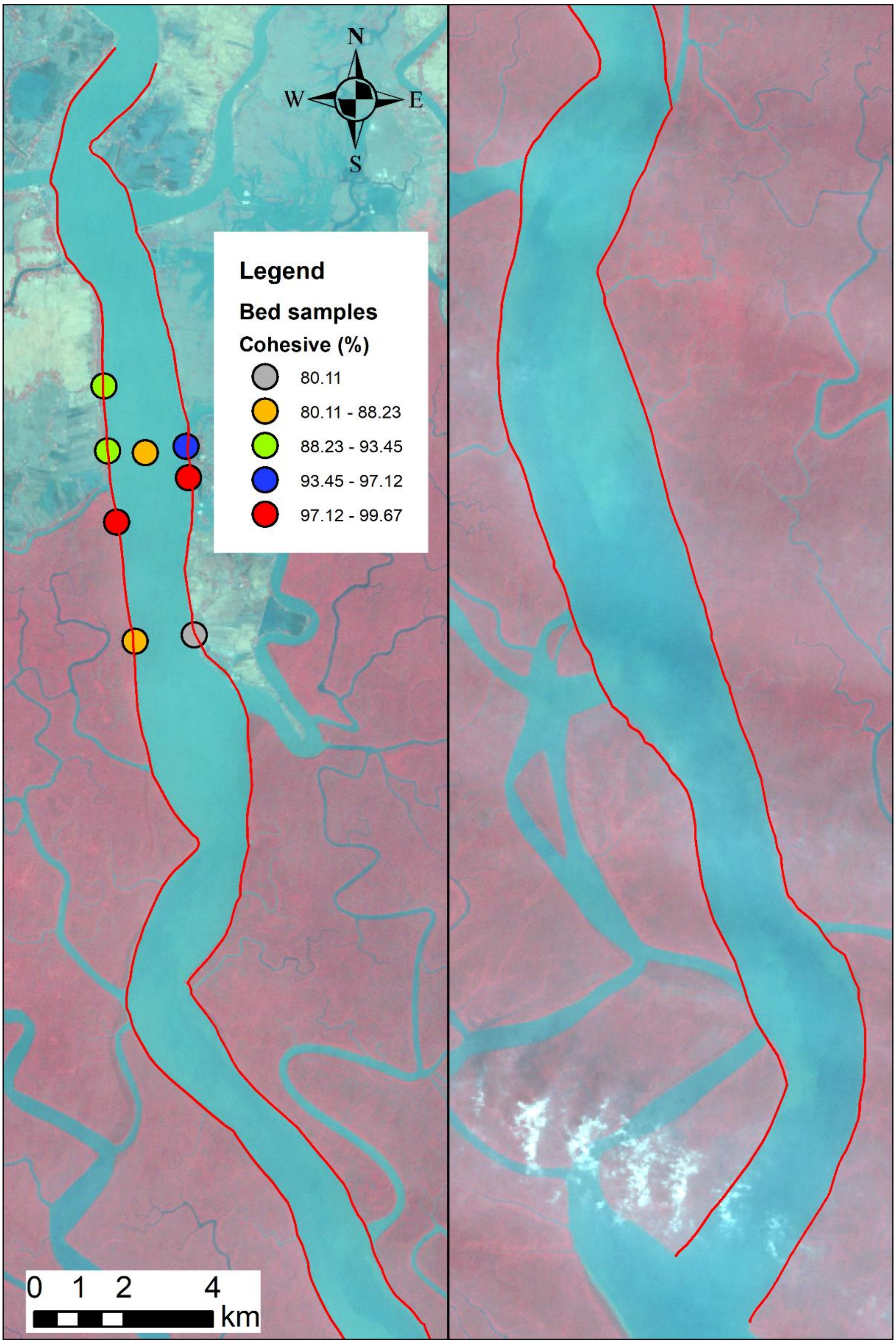


Figure 3-5 Measured sediment fraction of bed sample for Sibsa River. The colours indicate the cohesive sediment content.

It was the intention to compile the bed samples into a single map showing a colour code for the cohesive content and the d_{50} shown as text, but this has not yet been done for the Sibsa River. Part of the reason is that the downstream samples in Sibsa from the GRRP project show sand, but we do not have the data for the samples. These samples are very interesting, but it is difficult to do anything without the data files.

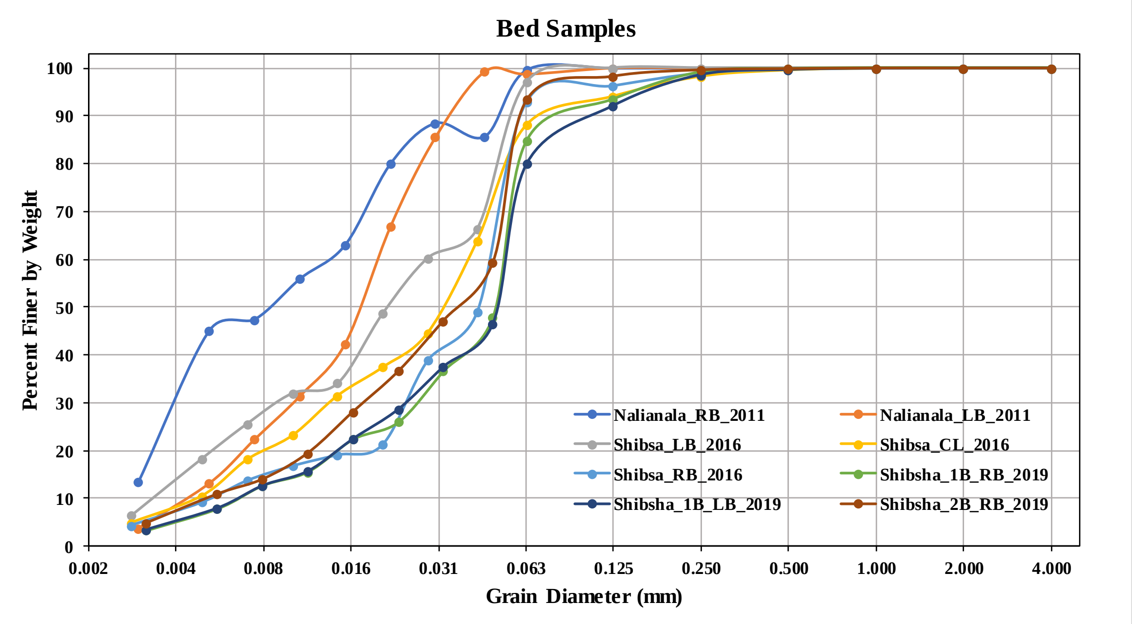


Figure 3-6 Sibsa River bed samples from 2011 to 2019 (February) collected by IWM.

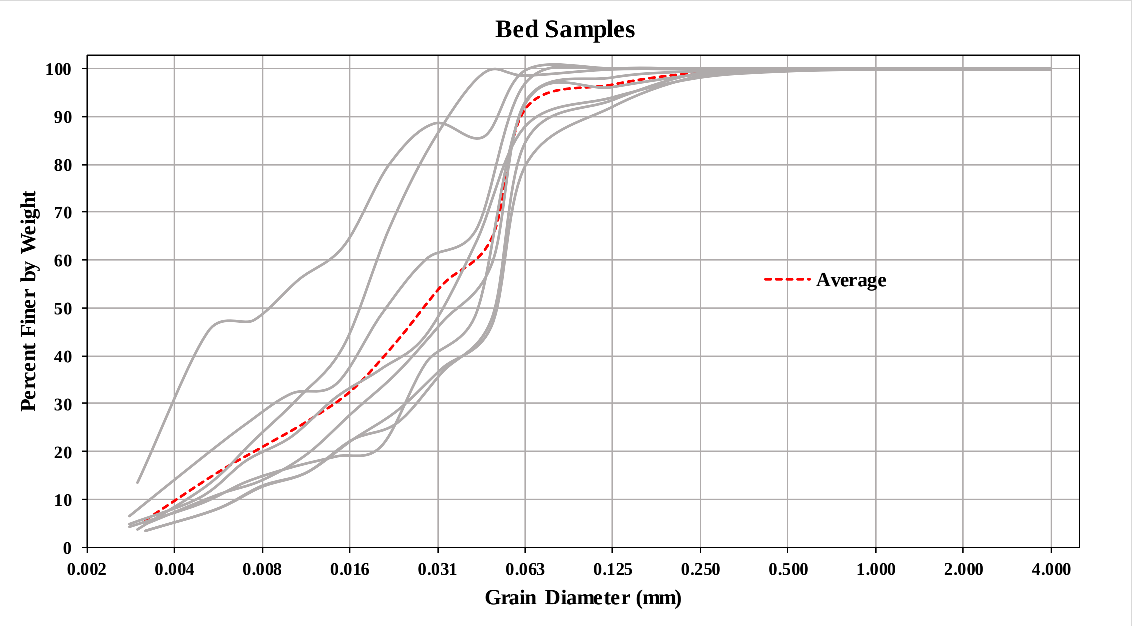


Figure 3-7 Sibsa River bed samples from 2011 to 2019 (February) with average curve.

The available bed samples for Sibsa River show consistently cohesive sediment dominated by silt. For the Pussur River (DHI and IWM, 2020a) we found a consistent sandy core of the river, which we believe can be traced to the Gorai River. However, the Sibsa River does not have a clear connection to the Gorai River or to any other potential sand source.

Some samples in the Sibsa River are sandy in the downstream end of the river (see Figure 3-3). However, we do not have the particle size distributions available for those samples. This is an unfortunate shortcoming for the Sibsa River model development.

3.4 Suspended sediment data

Suspended sediment concentration data was collected in 2016 at Nalian. Data was also collected during 2019 for the present project at Nalian.

Table 3-5 Suspended sediment concentration data for Sibsa River.

Bed sample data collection year	Sources
2011	No data
2016	CEIP-1
2019	Primary data (present project)

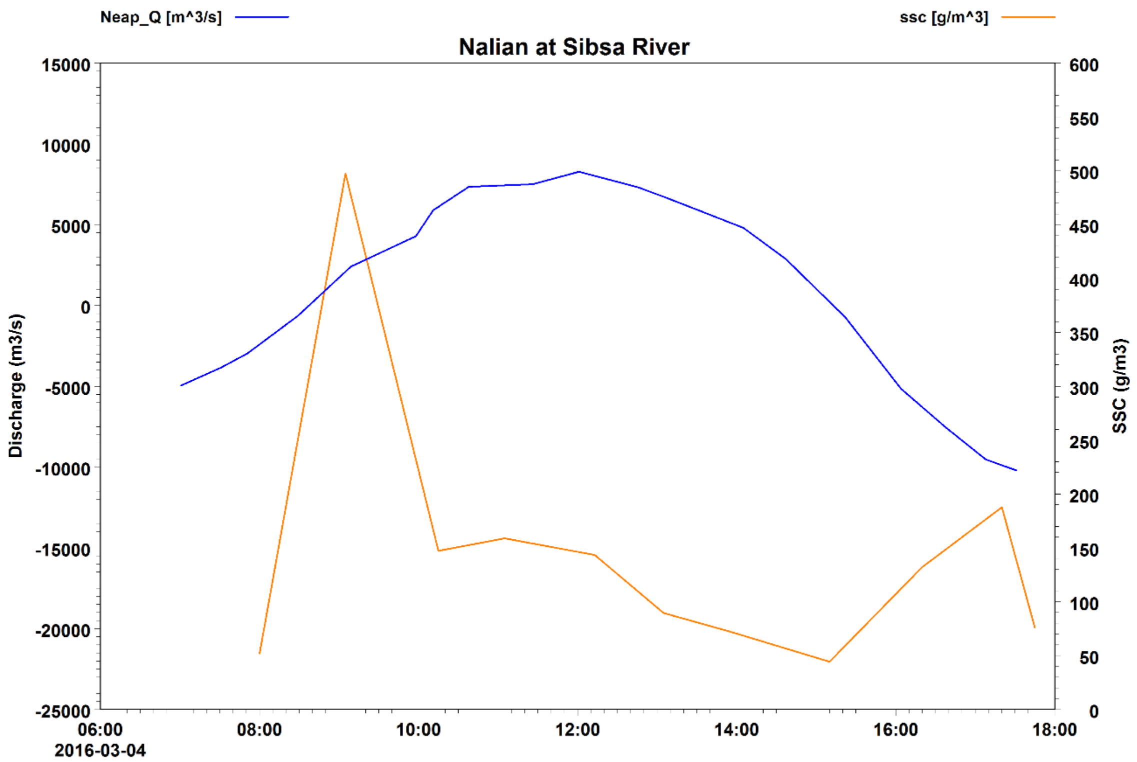


Figure 3-8 Discharge and sediment concentrations from 2016 during neap tide at Nalian.

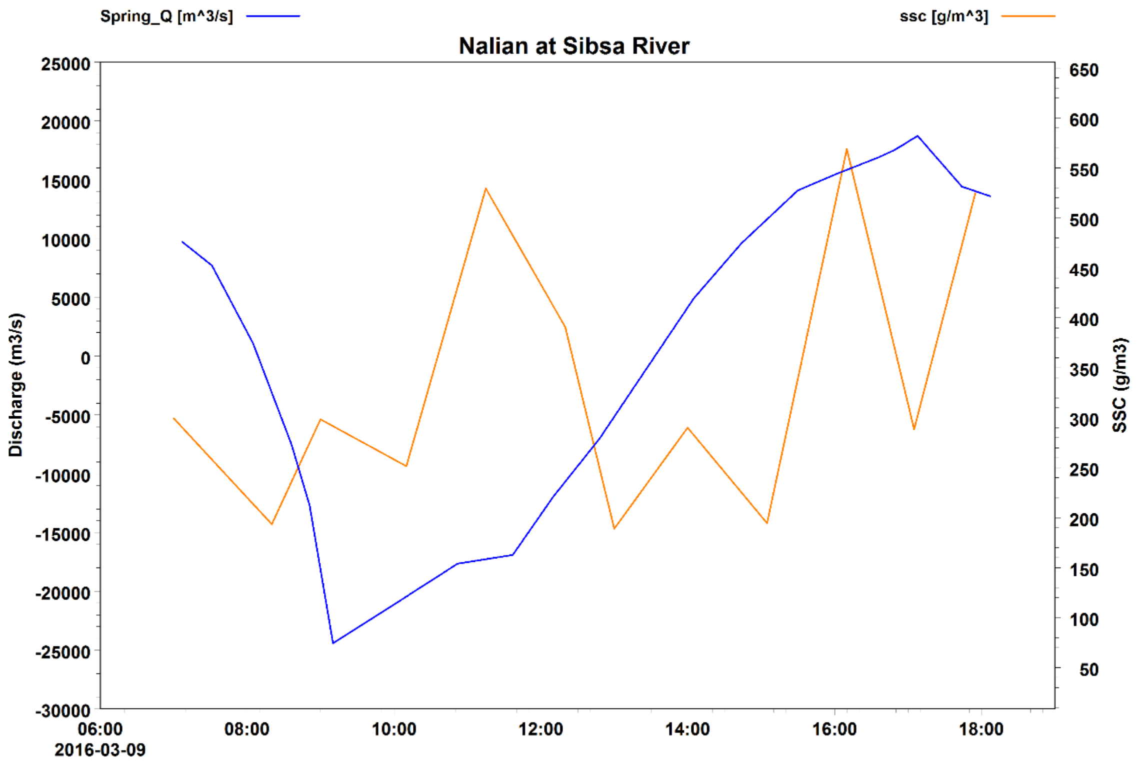


Figure 3-9 Discharge and sediment concentrations from 2016 during spring tide at Nalian.

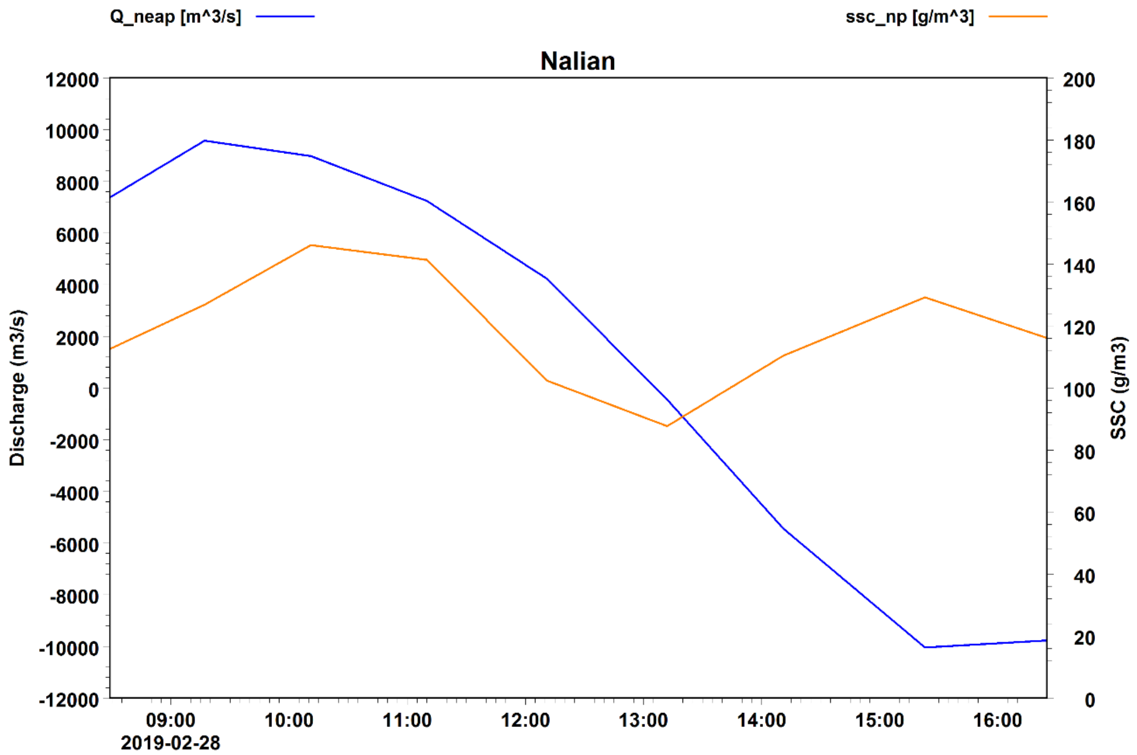


Figure 3-10 Discharge and sediment concentrations from 2019 during neap tide at Nalian.

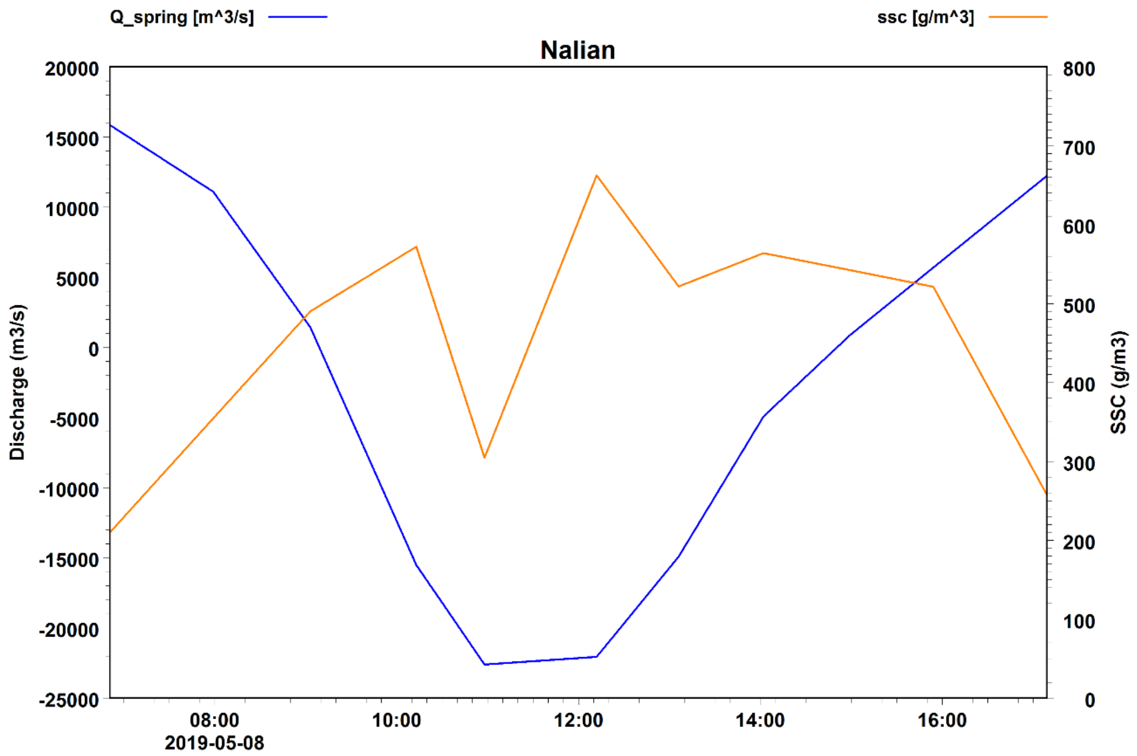


Figure 3-11 Discharge and sediment concentrations from 2019 during neap tide at Nalian.

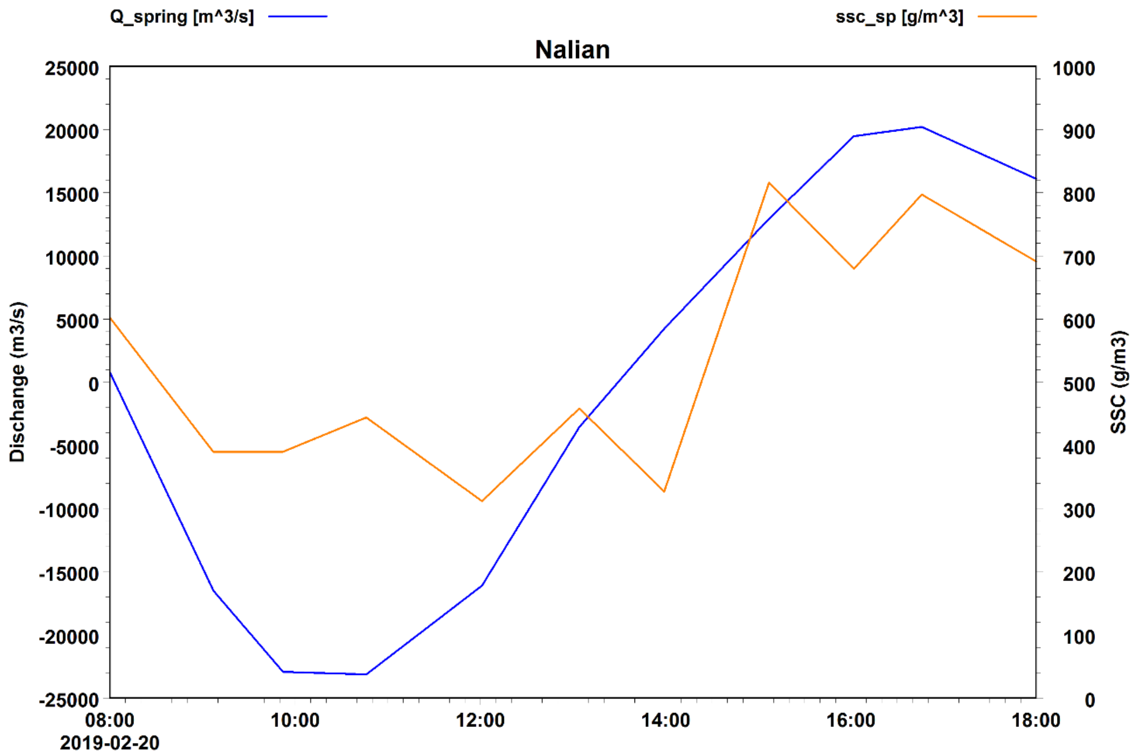


Figure 3-12 Discharge and sediment concentrations from 2019 during spring tide at Nalian.

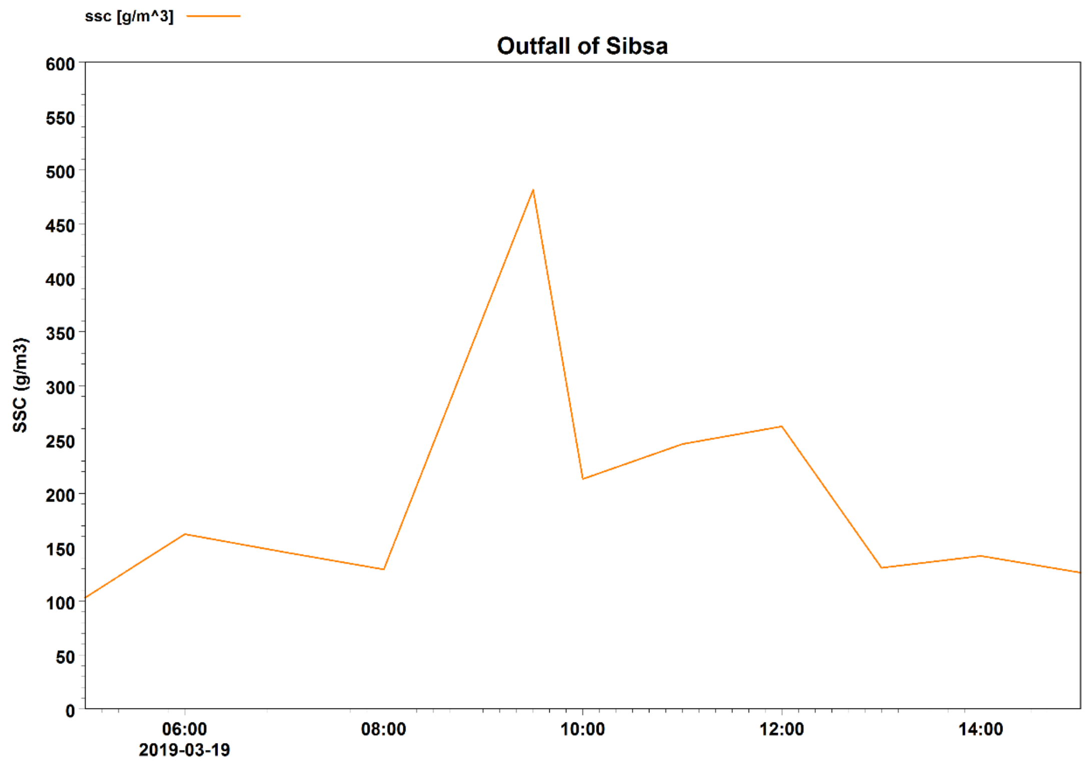
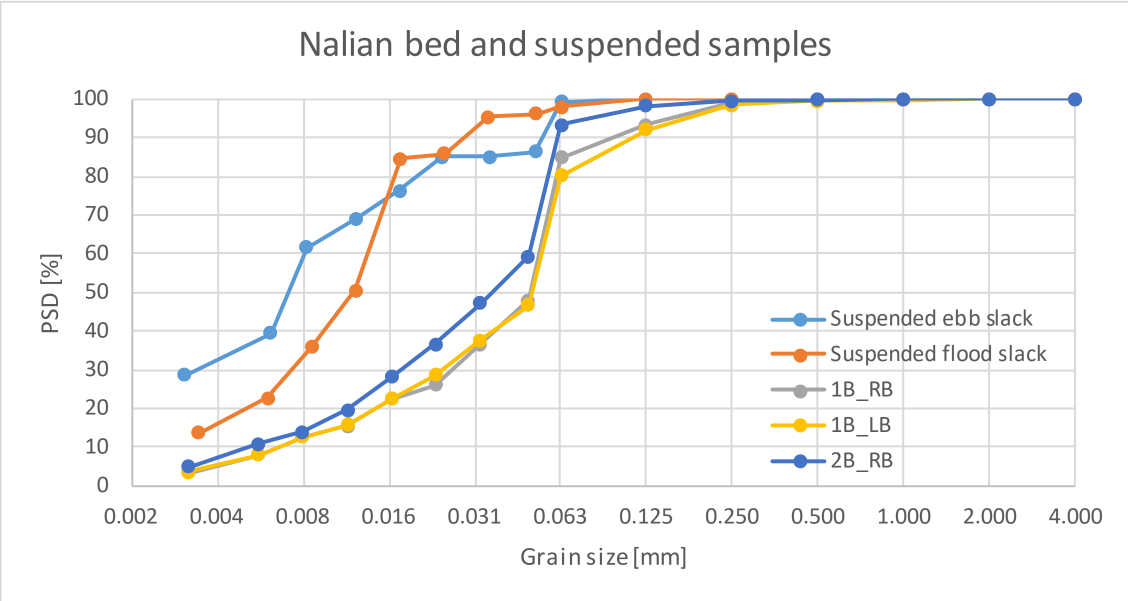


Figure 3-13 Sediment concentrations from 2019 at Akram Point in Sibsa River. The discharge was not measured at this location, and the 2019 SWRM was not available when the data was processed.

3.5 Suspended sediment particle size distribution data

Suspended sediment particle size distribution data was collected by IWM in 2001.



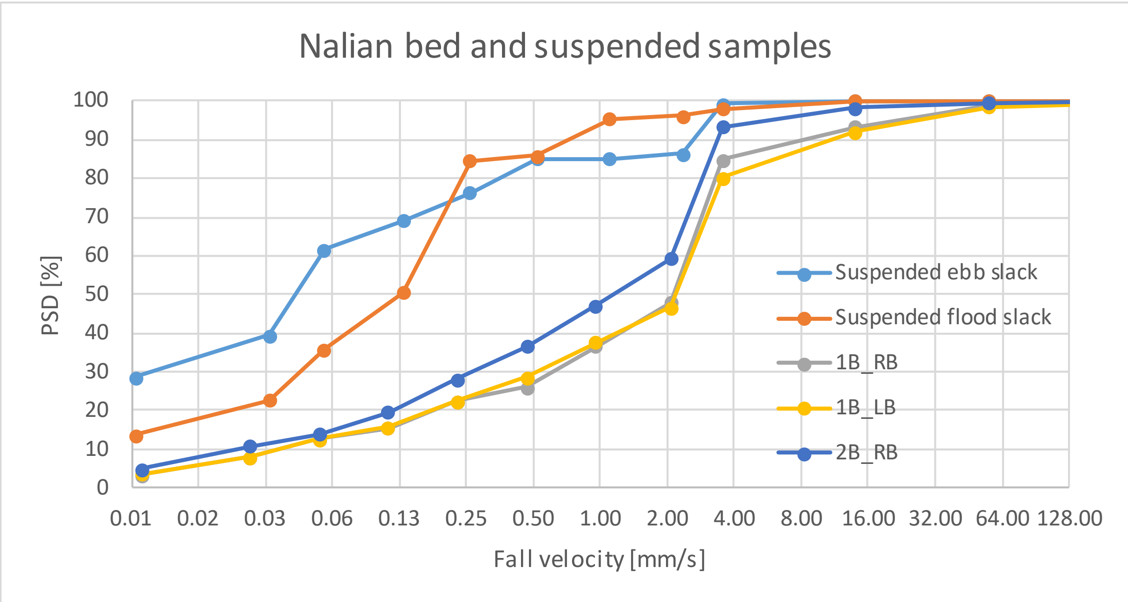


Figure 3-14 Suspended sediment particle size distribution at Nalian (IWM, 2001) compared to 2019 bed samples at the same location. Top: As a function of grain size, bottom: As a function of fall velocity calculated from Stokes' Law.

The data shows that the sediment in suspension is finer than the sediment in the bed. The suspended samples were from ebb and flood slack, and hence we would expect them to be finer than for the more relevant ebb and flood peaks. However, we have no data for the high velocities, so we continue in the following based on the slack tide observations.

The bed sand suspended median grain sizes are very different, roughly 0.008 mm for the suspended sediment versus 0.05 mm for the bed samples. The bed samples have a median fall velocity around 1 mm/s, while the suspended samples show around 0.1 mm/s (rough numbers). This suggests that a representative fall velocity should not be 1 mm/s if wanting to correctly simulate sediment concentrations. However, 1 mm/s is representative for the bed samples. Cohesive sediment with a fall velocity of 0.1 mm/s has a settling time through 20 m water longer than the tidal cycle and will therefore have very limited morphological activity. Indeed, we also observe that the finest cohesive sediment is hardly present in the bed samples.

Ultimately the analysis suggests that it is difficult to model the cohesive sediment with one representative fall velocity if wanting to correctly reproduce both bed levels and sediment concentrations. The single fraction model fall velocity has been selected from bed samples and the erosion function adjusted to obtain the correct bed level changes, but at the cost of not getting the best reproduction of sediment concentrations.

3.6 Historical bank lines from satellite imagery

In the study area, nine cloud-free scenes of Landsat imagery were acquired for the period of 1988–2019 from the Earth Explorer database of the U.S. Geological Survey, which covers the meso-scale modelling river system considered in the project. The time of acquisition of the images was mainly during the dry season from November to February as there were no clear images during other seasons. All the extracted riverbank lines are presented in Figure 3-15 to Figure 3-19 for the Sibsa River.

Polder 32 was largely affected due to erosion during the period.

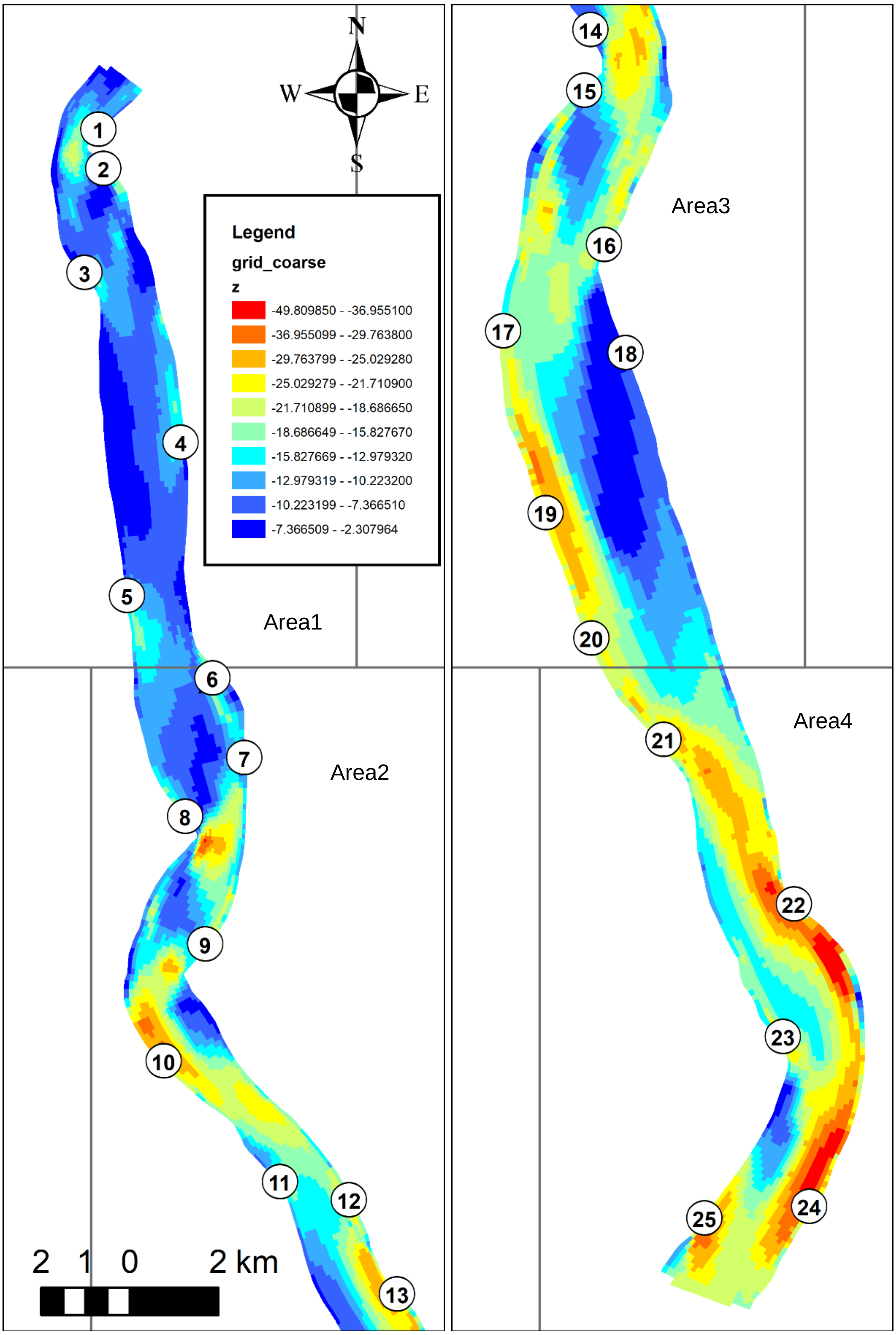


Figure 3-15 Identification of 25 eroding banks along the Sibsa River, and sub-division into four area for detailed presentation of the eroding banks.

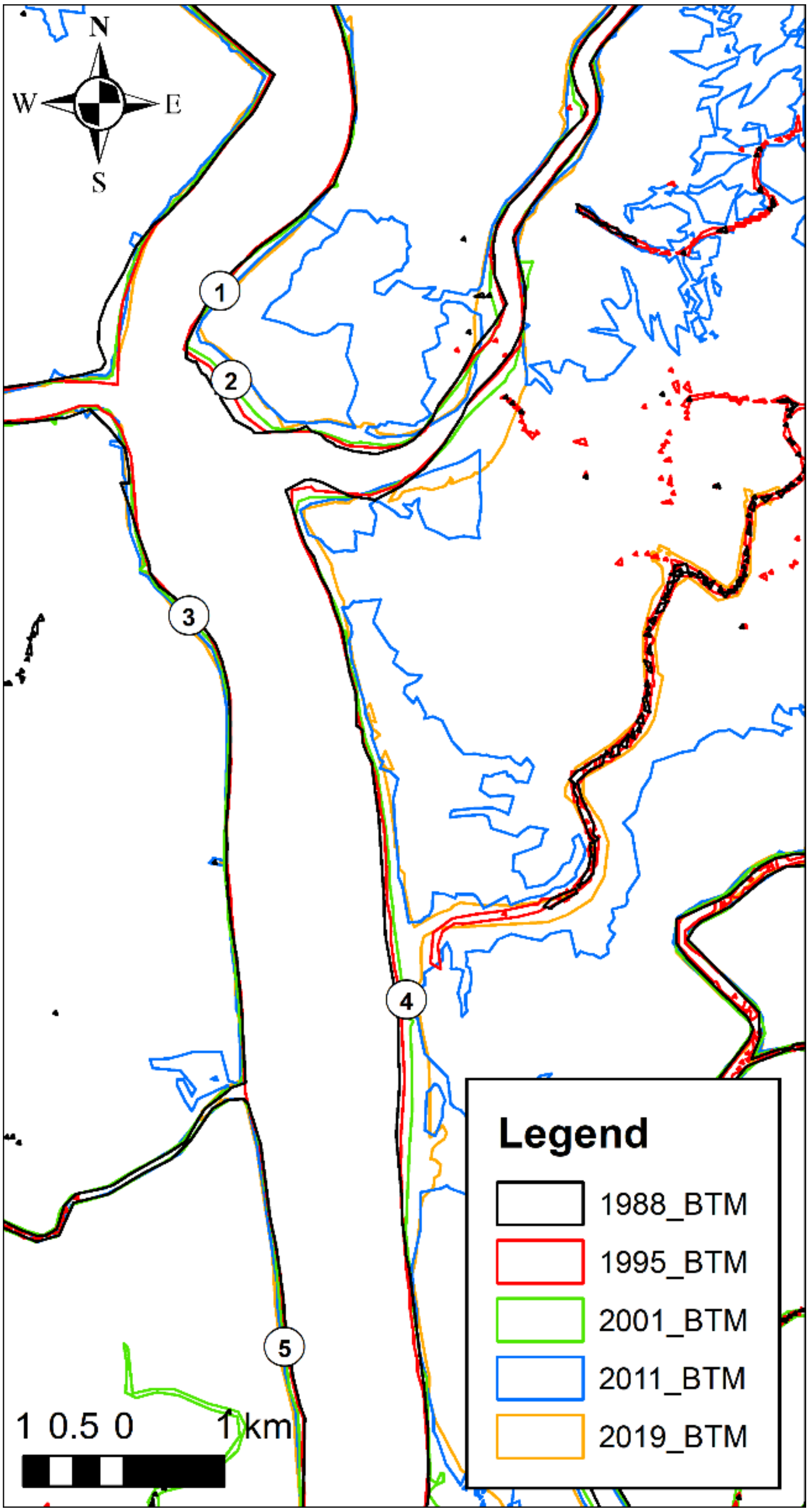


Figure 3-16 Eroding banks in Area1.

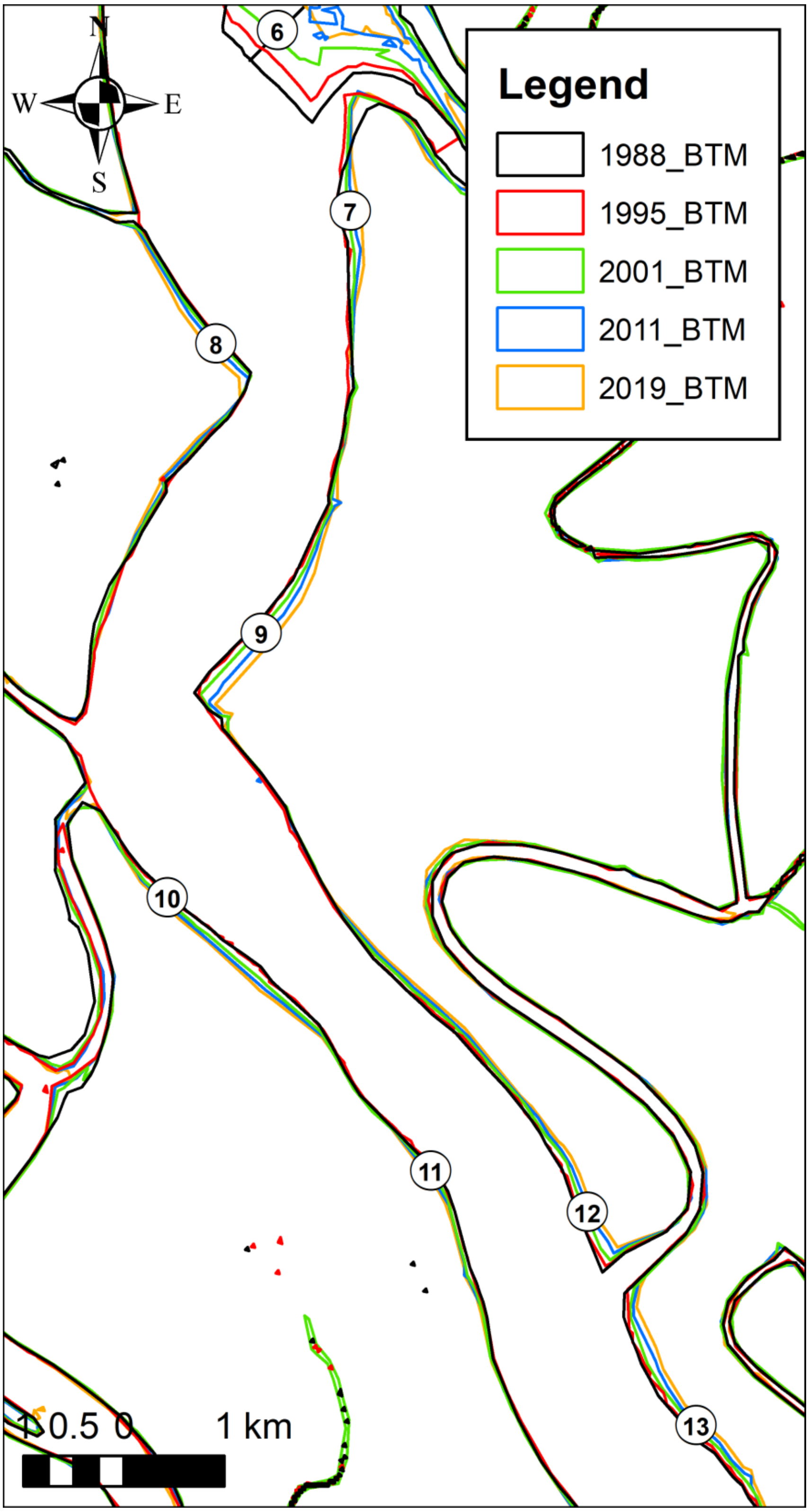


Figure 3-17 Eroding banks in Area2.

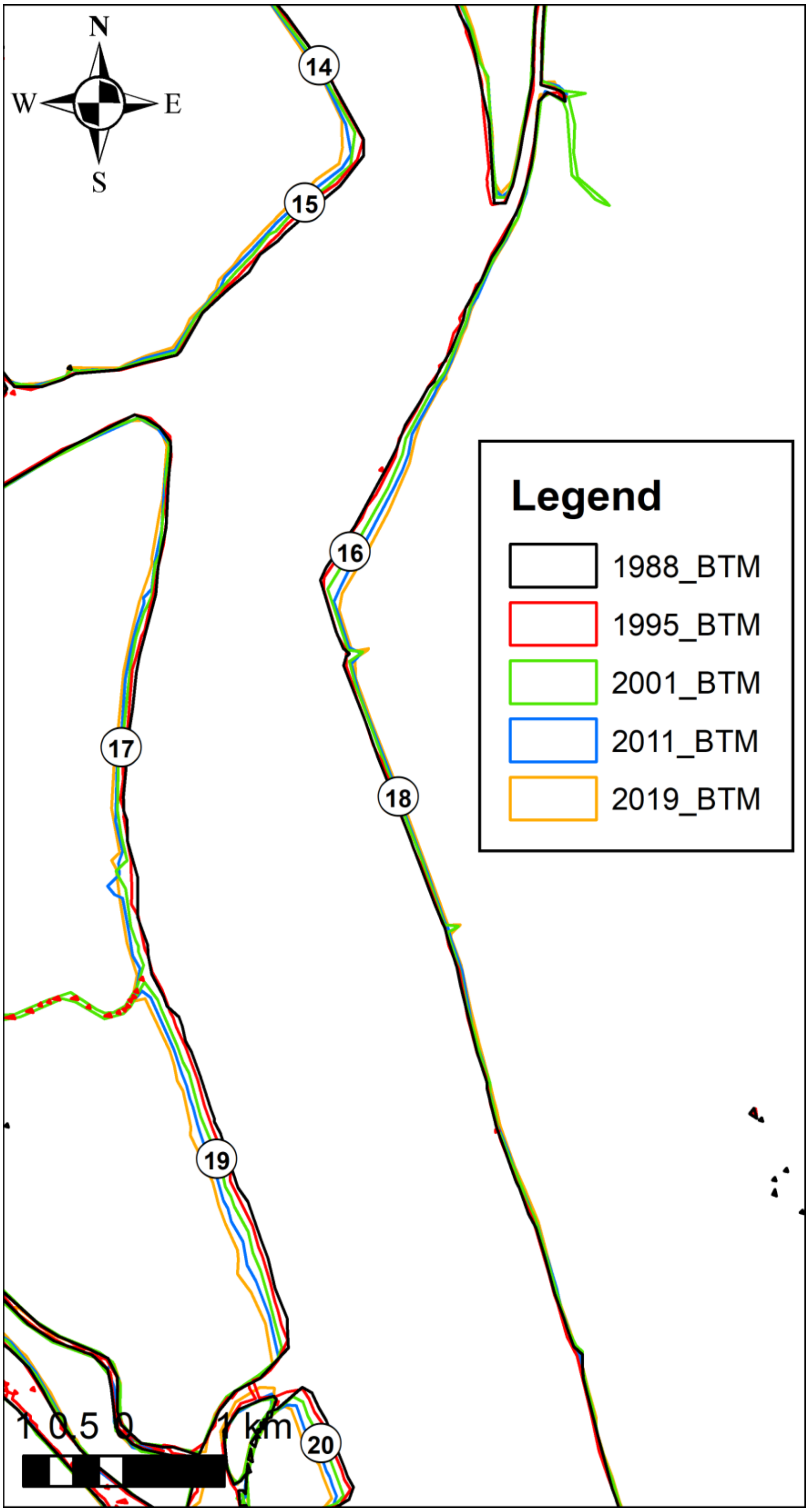


Figure 3-18 Eroding banks in Area3.

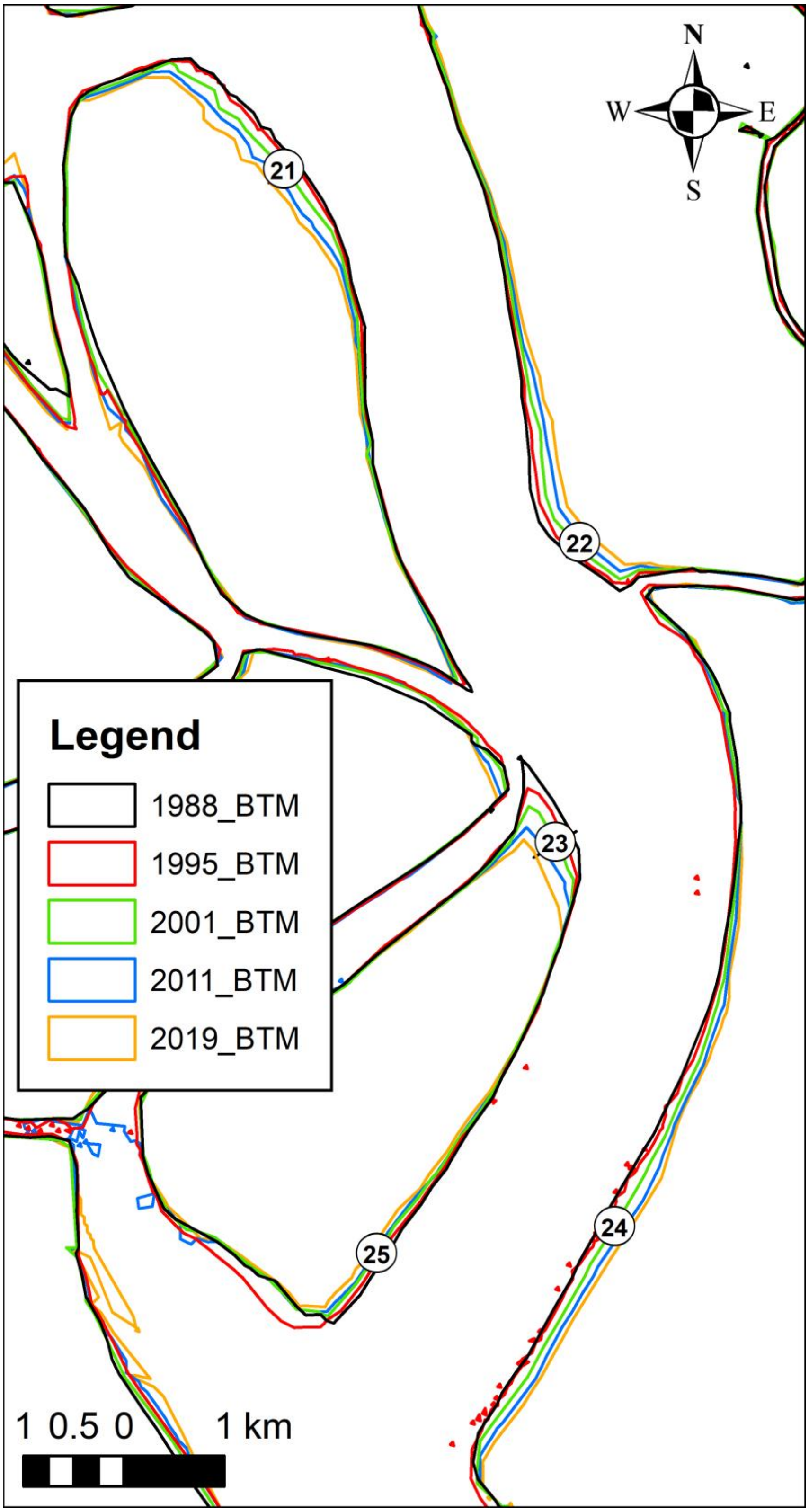


Figure 3-19 Eroding banks in Area4.

The bank lines are shown in local areas in Figure 3-16 to Figure 3-19:

- The data shows very consistent bank retreat
- The eroding banks are almost always outer bends with deep water
- Bank accretion is not modelled, but we note that all accreting banks have high bed levels and are located favourably to deposition
- The bank retreat rates are similar along the river

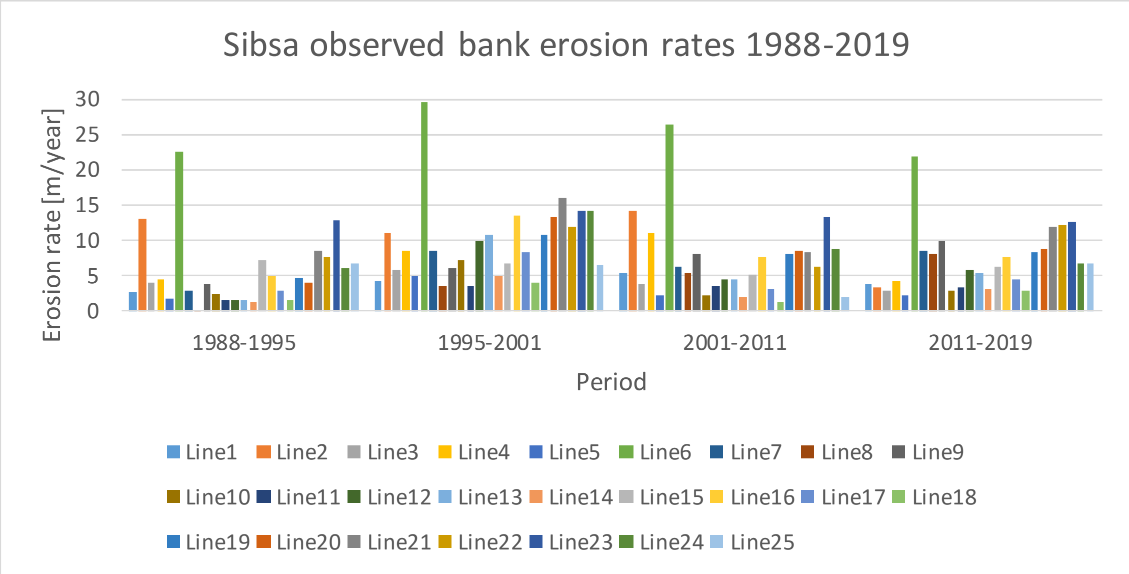


Figure 3-20 Erosion rate over time for 25 identified eroding banks.

Along the river we selected 25 eroding banks and estimated the annual erosion rates for four sub-periods 1988-2019, see Figure 3-20. The results show some variation in the erosion rates over time and for the different bank reaches. The temporal variation in erosion rates is not very strong (may be due to too long time periods), but we do see high erosion rates in 1995-2001 and lower erosion rates in 1988-1995.

Almost all the eroding banks are at outer bends, the exception being no. 18 which is located between the bank and the largest bar in the Sibsa River. The Landsat images show consistent erosion of this bank, but the bank erosion rates are the lowest among the banks with an average of 2.5 m/year. Nonetheless bank 18 is consistently eroding, which makes sense because there is a flood channel between the bar and the bank, which can erode the bank.

The bank erosion rates were highest in 1988-1995 and lowest in 1995-2001, while 2001-2019 saw similar average erosion rates.

The bank lines were processed into bank erosion by projecting along the normal vector from the 2011 bank lines to the 2019 bank lines. This converts the bank lines into bank erosion as a function of the northing coordinates along the banks. The Sibsa riverbank erosion was processed to exclude the side channels, and the eroding banks in the model were defined to exclude the side channels.

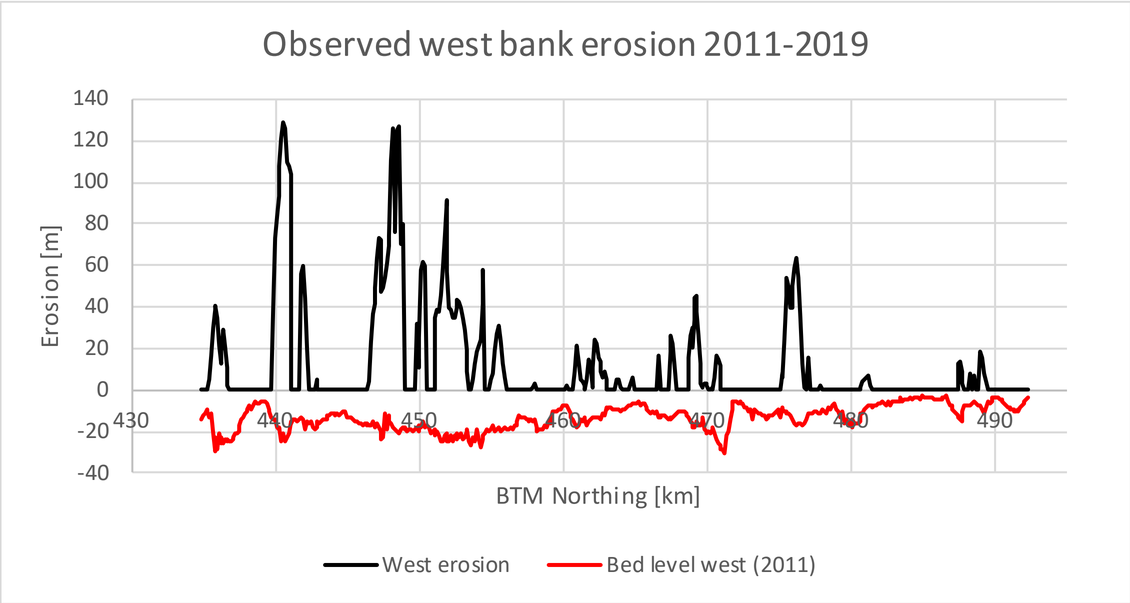


Figure 3-21 Observed bank erosion 2011-2019 along the west bank of Sibsa River as a function of the BTM northing coordinate along the bank.

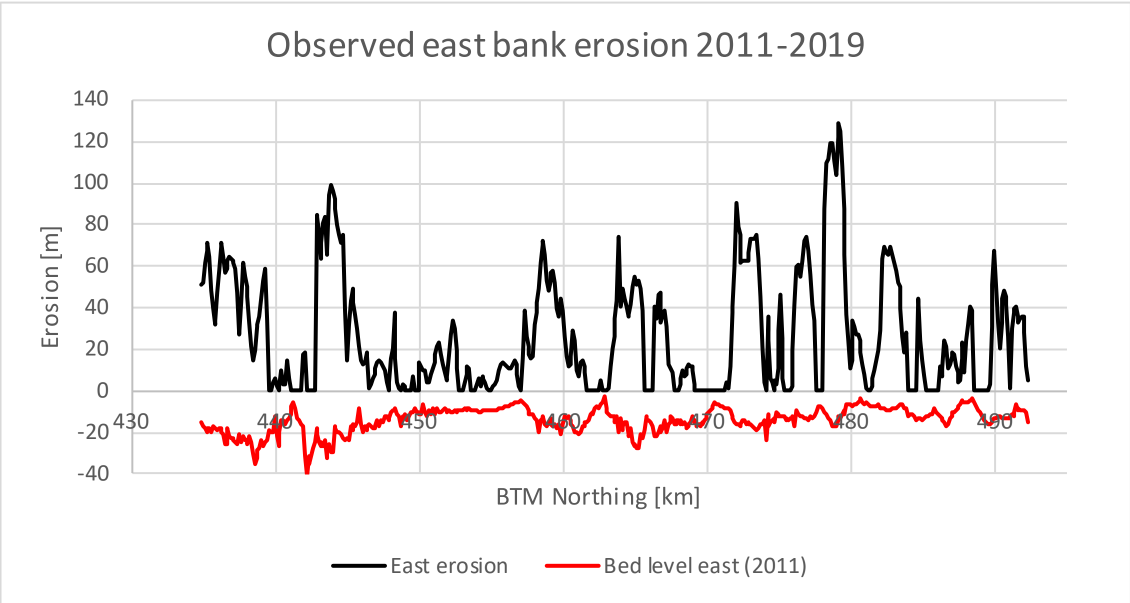


Figure 3-22 Observed bank erosion 2011-2019 along the east bank of Sibsa River as a function of the BTM northing coordinate along the bank.

The processed bank erosions in 2011-2015 and 2011-2019 are shown in Figure 3-21 and Figure 3-22.

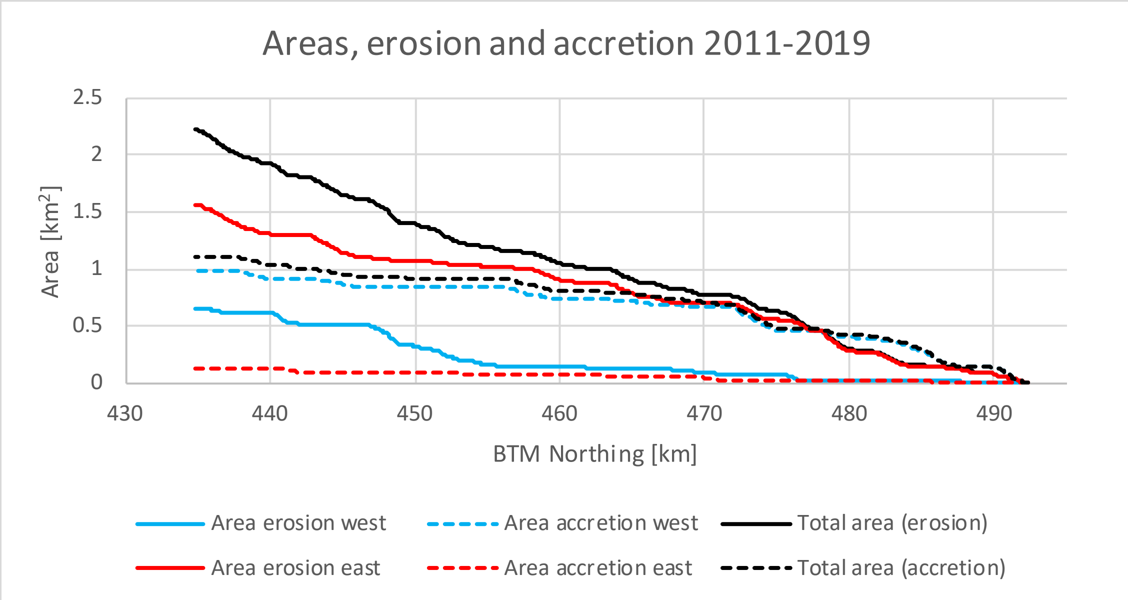


Figure 3-23 Area curves associated with bank erosion and accretion 2011-2019.

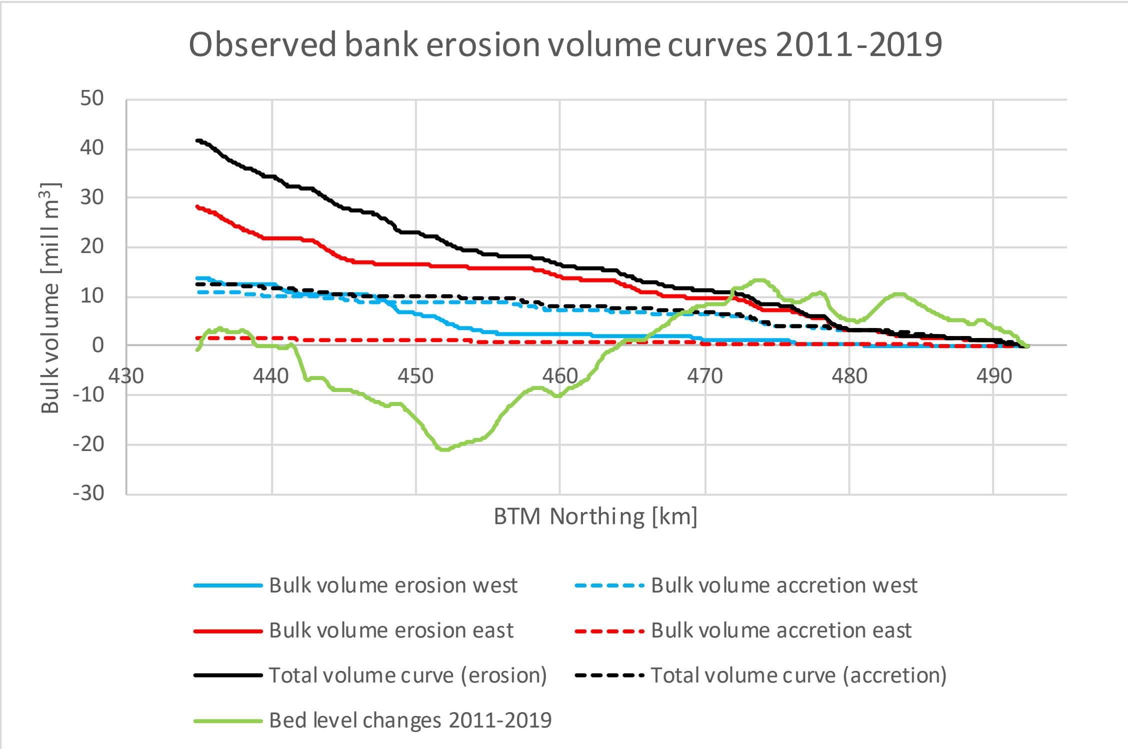


Figure 3-24 Observed bank erosion bulk volume curves compared to bulk volume curve from bed level changes for 2011-2019.

The eroded and accreted areas were calculated from the erosion and accretion curves and shown in Figure 3-23. It is interesting to note that the west bank experienced significant accretion exceeding erosion, while the east bank was dominated by erosion.

The bank erosion bulk volume curves are interesting because they tell us how much the eroded material will contribute to the bathymetry changes. The local eroded volume was estimated from the 2011 bathymetry at the bank:

$$Vol = E\,(H_b - z)\Delta s$$

Where H_b is the bank level (estimated 2 mPWD in the Sibsa model), z is the local bed level at the bank, E the erosion [m] and Δs the local grid spacing [m]. The volume curve is the integration of the eroded volumes along the bank, starting from upstream. Hence the downstream volume in the integrated bulk volume curve is the total eroded bulk volume.

Figure 3-24 shows a comparison of the bulk volume curves associated with bed level changes and bank erosion in the period 2011-2019. It is seen that the bulk volumes associated with bank erosion are higher than the volumes associated with bed level changes.

In this model we have used the same porosity for the bank material and bed material (0.5). In reality, the bank material is more compacted than the bed material, which means that the eroded material will fill an even larger part of the sediment budget for 2011-2019.

Bank accretion was processed separately from the observations, although bank accretion is considered a passive process in the model. We can see from the figures that bank accretion amounts to half the eroded area in 2011-2019 but only around 25% of the volumes due to the generally much shallower water at accreting banks compared to eroding banks.

We conclude that the sediment bulk volumes associated with bank erosion are significant compared to the bulk volumes associated with changes to the bathymetry.

4 Model development

4.1 Grid and bathymetry

The two rivers, Pussur and Sibsa, were originally modelled in one single model. However, this idea was abandoned in the present study because we can make simpler models. The interaction between the rivers can be handled via boundary conditions from the SWRM.

The river system has some influence from floodplain (e.g. mangrove forest and outside the polder areas), which was identified from the available DEM elevations. The MIKE 11 model (SWRM) also shows significant floodplain along both rivers, which is reflected in the output from the MIKE 11 model.

Two versions of the Sibsa River model were adopted in the development:

- Fine grid with floodplain
- Coarse grid without floodplain

The fine grid model was used for the HD calibration and sediment concentrations calibration. The fine grid became too cumbersome for the morphological hindcasting 2011-2019, which was not originally planned. We also realized that the floodplain around the Sibsa River does not play a significant role. In order to speed up the 2011-2019 hindcasting, a coarse grid model was developed.

4.1.1 2011 model

The 2011 model was developed from the 2011 bank lines and the 2011 bathymetry.

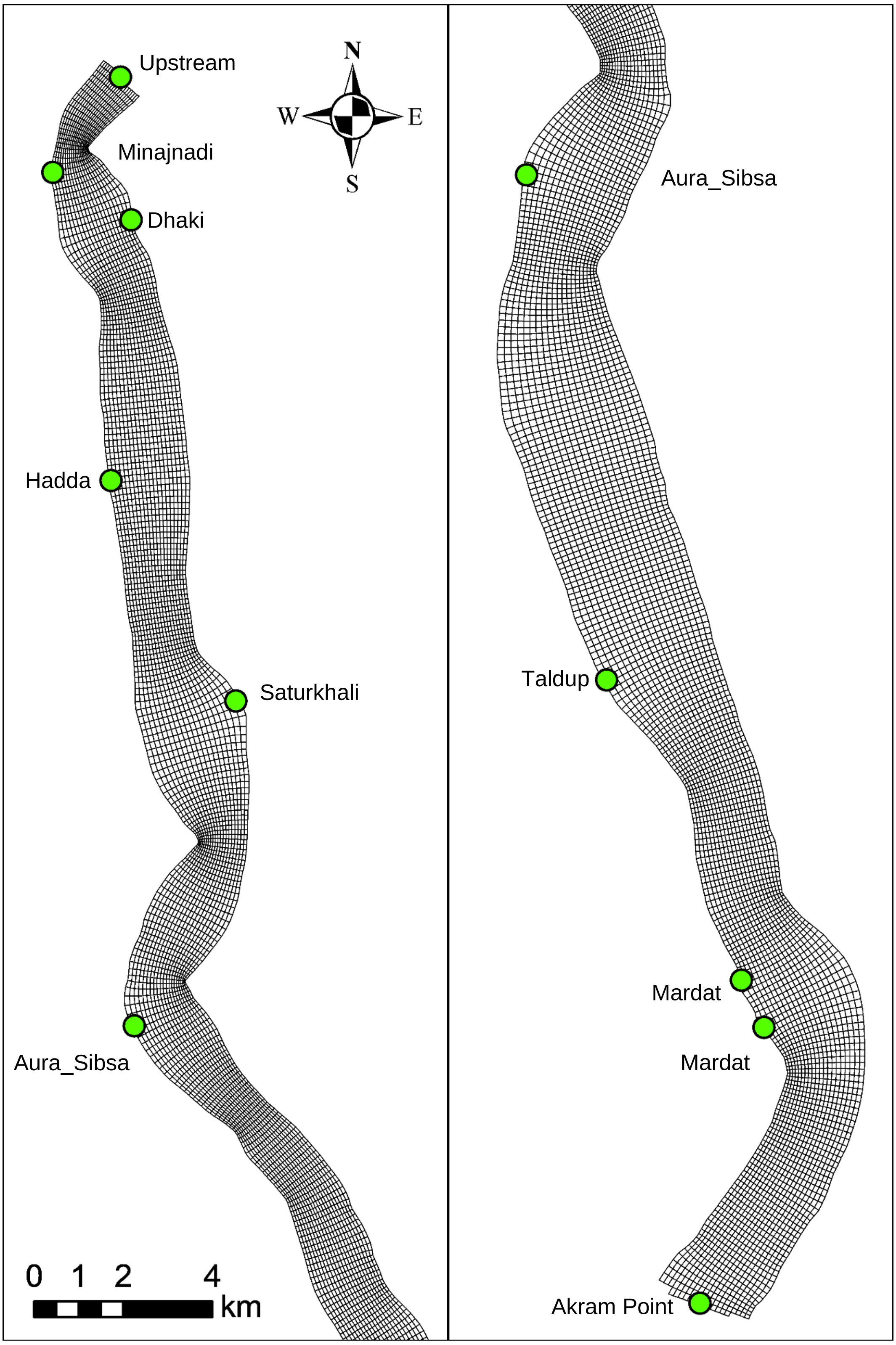


Figure 4-1 Sibsa River curvilinear 500x20 grid 2011 with boundary locations shown to avoid too many unnecessary figures.

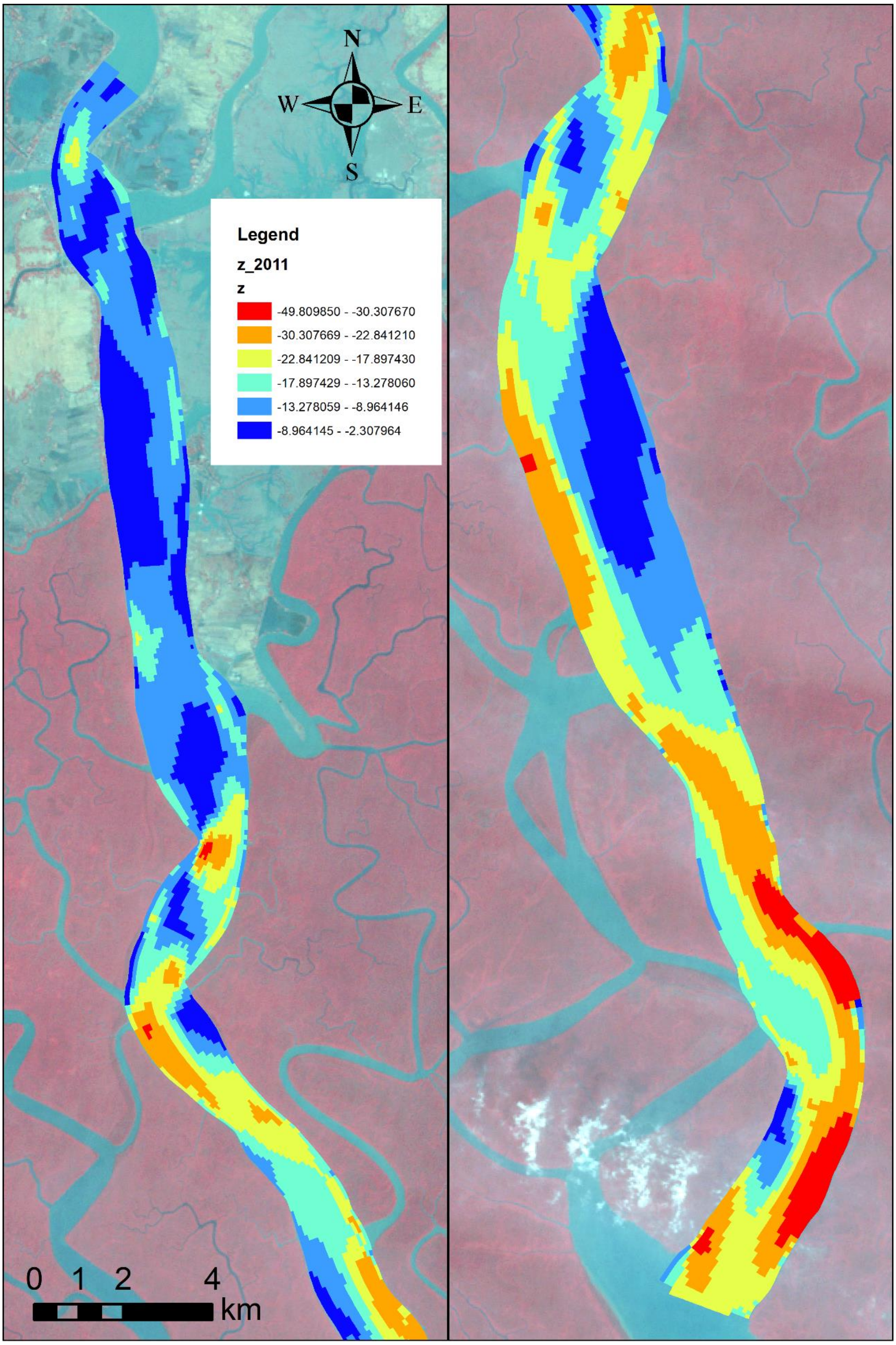


Figure 4-2 Sibsa River curvilinear bathymetry 2011.

Figure 4-1 shows the 500x20 curvilinear grid. The location of secondary channels represented by lateral flows (source points) is also shown in this figure to avoid too many figures. The 2011 bathymetry is shown in Figure 4-2.

4.1.2 2019 model

The 2019 Sibsa River model was used for 2019 validations and scenario simulations starting from 2019 (initial condition).

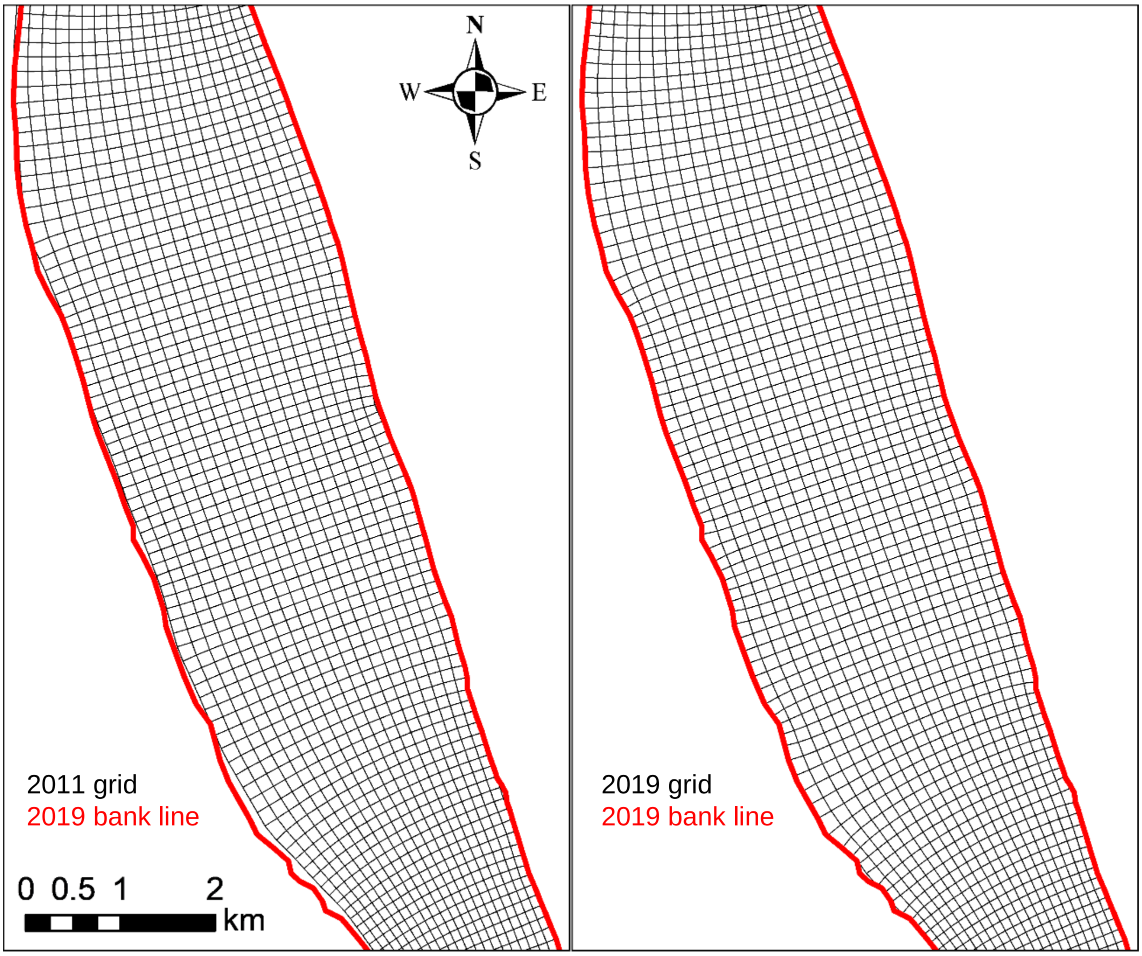


Figure 4-3 Illustration of the differences between the 2011 and 2019 grids, which cannot be identified without looking at the details. This is the large bend in the downstream end with consistent erosion since 1988 along the western bank. The 2019 grid conforms to the 2019 bank line, as seen in the figure. Even at this scale it is necessary to look carefully to see the differences between the grids (hint: western bank in the downstream end).

A local detail of the two grids is shown in Figure 4-3. Graphically it is very difficult to see any difference between the 2011 and the 2019 grids. However, the 2019 grid has the 2019 bank lines, which are important to account for, especially in the bank erosion forecast scenario simulations.

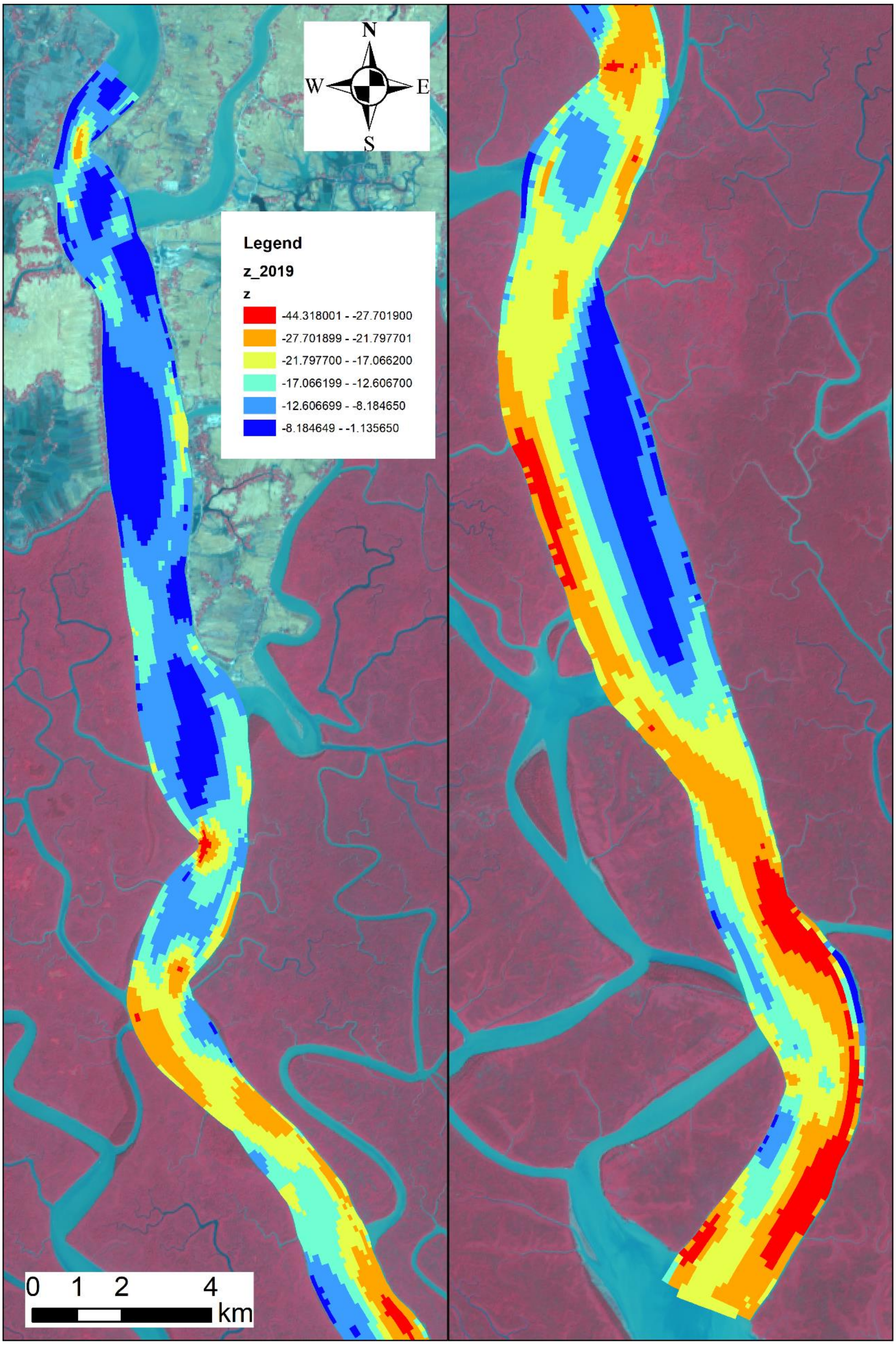


Figure 4-4 2019 bathymetry on 2019 grid.

4.2 Boundary conditions (hydrodynamic model)

The Sibsa River model has upstream discharge and downstream water level boundary conditions. The upstream boundary discharge was collected from the calibrated and validated South West Regional Model (SWRM). The downstream boundary water level was extracted from the combined river system model which has a water level boundary at Hiron Point.

The side channels discharges were added as source points (adding and removing water to reflect the interaction with the side channels) in the models. It is essential to include the side channels in the hydrodynamic model, as the flow exchanges with these side channels are significant. All the sources were extracted from the South West Regional Model provided by IWM.

Table 4-1 Boundary conditions for the Sibsa model.

X [m]	Y [m]	Type	Name	Chainage [m]
440645	492354	Q	Sibsa	10650
448653	434847	H	Sibsa	75000
439126	490221	Q	Minajnadi	15750
440429	483304	Q	Hadda	3000
440951	471068	Q	Aura_Sibsa	500
444761	460159	Q	Aura_Sibsa	19250
446561	448834	Q	Taldup	18700
449586	442092	Q	Mardat	3445
450098	441037	Q	Mardat	5400
440880	489150	Q	Dhaki	13500
443232	478360	Q	Saturkhali	27500

The boundary locations are tabulated in Table 4-1 and also shown graphically in Figure 4-1.

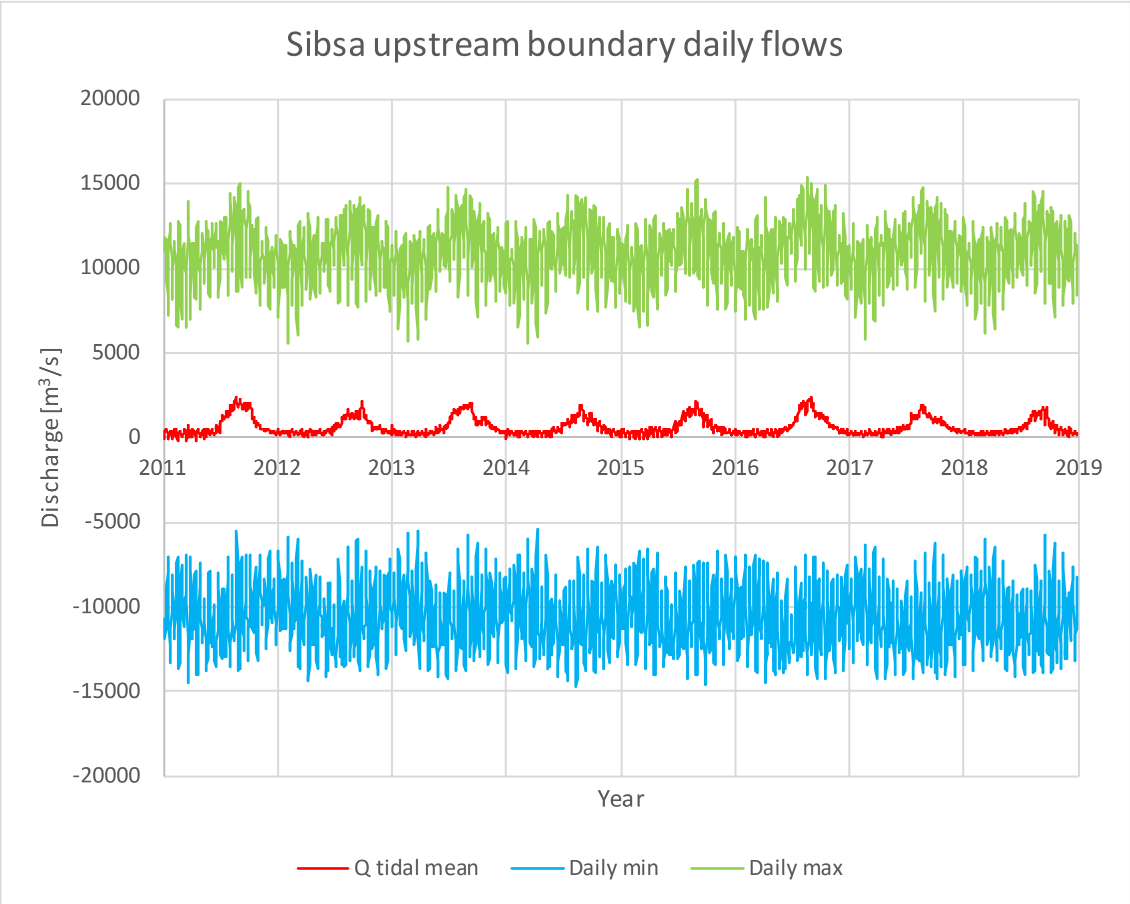


Figure 4-5 Daily minimum, maximum and mean flows 2011-2019 upstream boundary in the Sibsa River model.

The time-series cover 8 years, and therefore the full time series is not meaningful graphically due to the many tidal cycles during the period. One meaningful analysis is to look at the daily minimum, maximum and mean flow, which is shown in Figure 4-5 for the upstream end:

- The daily mean flow has a clear seasonal signal, with no mean flow in the dry season (i.e. tidal) and a clear and sizeable mean flow during the monsoon
- The various years 2011-2018 have similar signals

The tidal discharges at the upstream end are up to about 15,000 m^3/s, so the monsoon net flow at the upstream end is much smaller than the tidal flow.

The Sibsa River has a very low net flow compared to the tidal discharges, also when we compare to Pussur, which has much more net flow. This aligns with the consensus that the Sibsa River is an estuary with little freshwater flow (also referred to as a dead end in this report).

4.3 Hydrodynamic calibration and validation

The hydrodynamic model was calibrated with field data during 2011 both dry and monsoon season. The validation was done for 2016. The locations of the field data are shown in Figure 3-2.

4.3.1 HD calibration 2011

The Sibsa River model was calibrated with a constant Manning M=50 $m^{1/3}/s$. The data did not justfiy a more detailed calibration, although the bed samples suggest that the downstream end is sandy, while the upstream end is cohesive. It is possible to calibrate the model with a resistance map but difficult to carry out with the available water level stations.

The downstream discharge stations are extremely valuable because they give an overall handle on the tidal prism, while we do not have a downstream water level station in Sibsa.

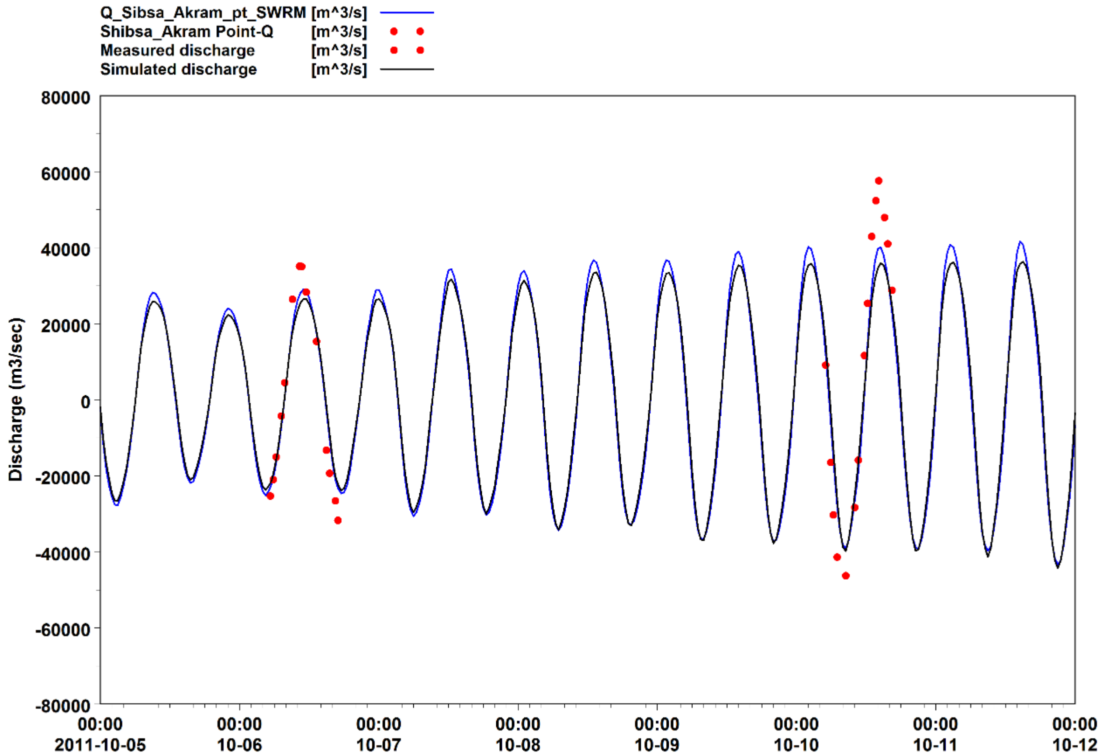


Figure 4-6 Discharge calibration at Akram Point in Sibsa River during the 2011 monsoon.

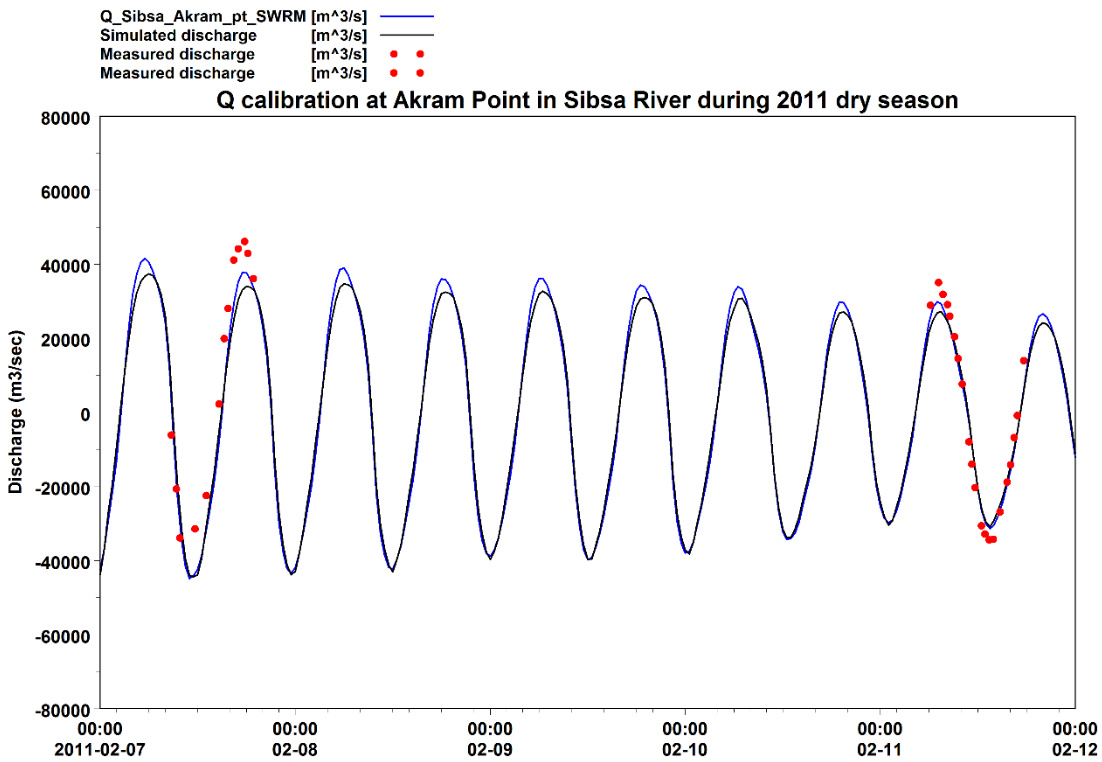


Figure 4-7 Discharge calibration at Akram Point in Sibsa River during the dry season (February).

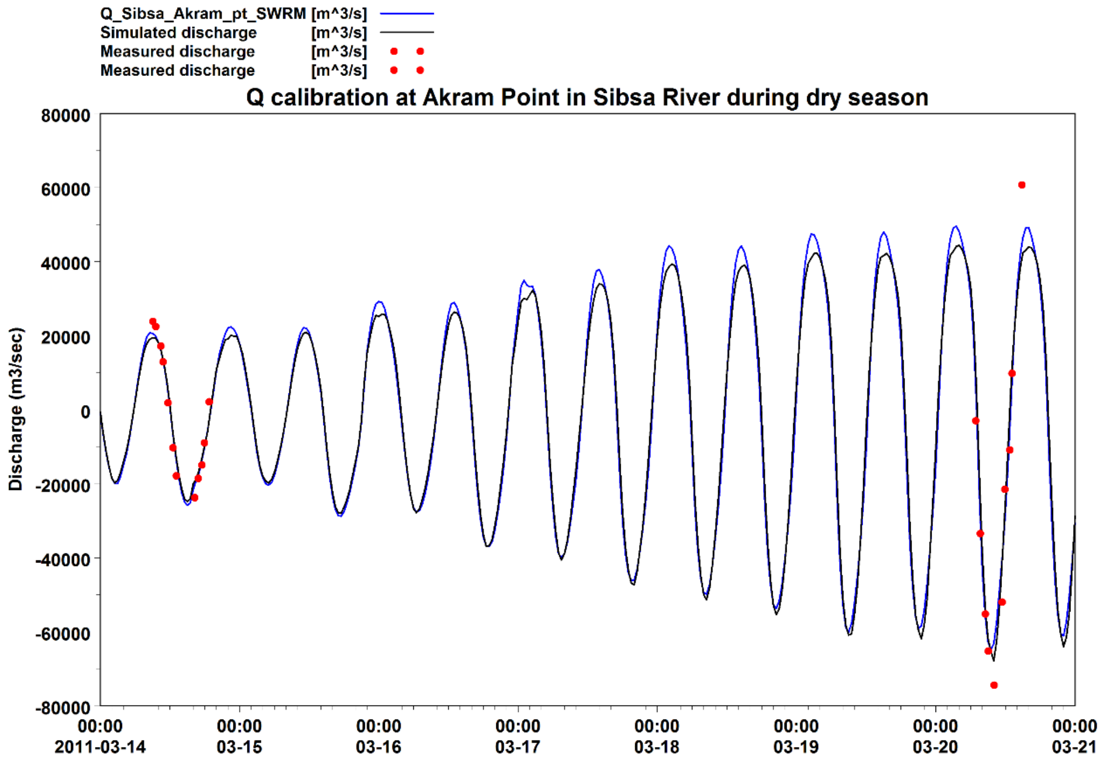


Figure 4-8 Discharge calibration at Akram Point in Sibsa River during the dry season (March).

Figure 4-6 to Figure 4-8 show the discharge calibration at Akram Point in Sibsa River during 2011 monsoon and dry season. The computed discharge is underpredicted for both flood and ebb flow and especially during spring flood. Underprediction is generally worse for ebb flow. Implications are discussed in Section 4.3.4.

4.3.2 HD validation for 2015

Water level observations are available in 2015 at Nalian. These are the only water level observations at this stage, while later revisions of this report will include the 2019 water level observations at Nalian.

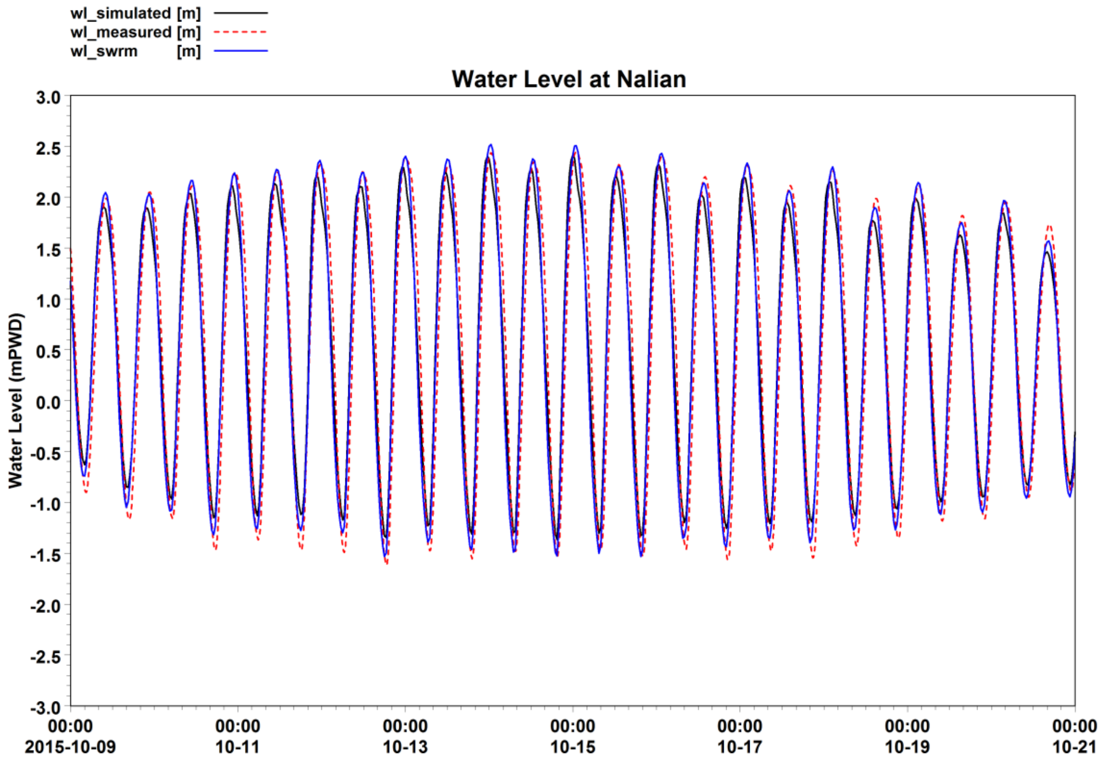


Figure 4-9 Water level validation at Nalian in Sibsa River during 2015. The results include the Sibsa model and the SWRM, and both validate convincingly against the Nalian water level observations.

Figure 4-9 compares the observed and simulated water levels at Nalian in October 2015. The simulated water levels agree very well with the observations, which further supports that the real problem with the Sibsa River model is the lack of floodplain flow (downstream of this location).

4.3.3 HD validation 2016

The calibrated model is now validated against 2016 data.

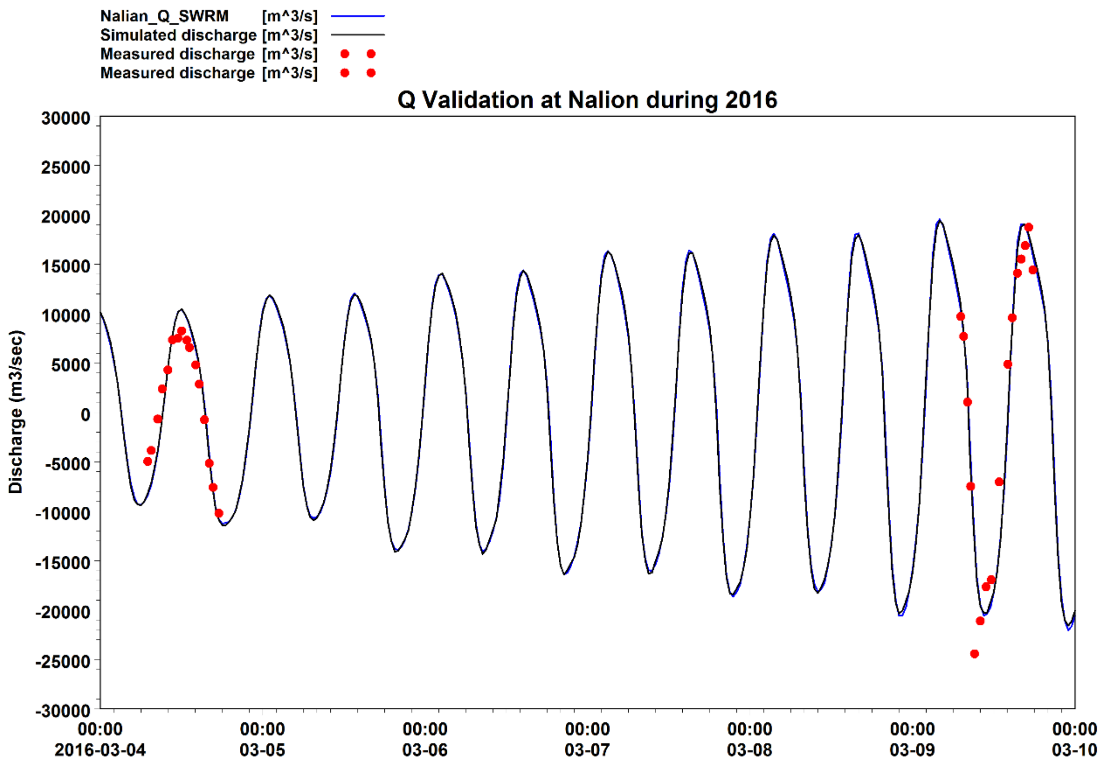


Figure 4-10 Discharge validation at Nalian in Sibsa River during 2016.

The hydrodynamic validation was done at Nalian for 2016 which is shown in Figure 4-10. The agreement is excellent, even though we know that further downstream at Akram Point we underpredict the discharge.

4.3.4 Summary of the HD calibration and validation

The Sibsa River model has some issues when we look at the calibration and validation of the model:

- Consistent underprediction of the Akram Point discharge
- No water level data available at Akram Point
- Nalian discharges show that both models, namely MIKE 21C and SWRM, correctly reproduce the observations at Nalian

The underpredicted discharge at Akram Point is problematic with potential implications for the modelled morphological behaviour. Considering that the boundary conditions for the MIKE 21C model come from the SWRM, it is no surprise that the MIKE 21C model inherits the too low Akram Point discharge from the SWRM.

We have looked at conditions further upstream in Sibsa, and it is possible that tidal prism is missing upstream of the northern boundary, which means that the upstream MIKE 11 discharge boundary has too low amplitude; too little water is going north and south at this location if there is a missing tidal prism upstream. However, this has been effectively dismissed with the validation against observed discharges at Nalian.

One of the conclusions – which is not new – from the overall study is that the Pussur-Sibsa system exhibits complex interaction between the two rivers. Among other things we know that the Sibsa

River is distinctly deeper than the Pussur River, so the tidal migration speed is faster in Sibsa compared to Pussur, which leads to exchange of flow between the rivers, making the Sibsa capture some of the Pussur tidal prism. The difference in migration speed is automatically accounted for in the SWRM, but the SWRM also underpredicts the Akram Point discharges in Sibsa.

The lack of water level observations downstream in the Sibsa River is not ideal. The tidal exchange between the downstream estuary and the Sibsa River is controlled by the water level variation. However, we have water level data at Nalian, which is validated in the model.

The underpredicted flows at Akram Point will influence the morphological model. Hindcasting shows a lot of sedimentation around northing 460 km, which was not observed. It is plausible that this is influenced by the too low simulated flows in the Sibsa River.

4.4 Sediment model

For the model we chose a single-fraction cohesive (silt) model.

The bed samples do not show a consistent picture of the sediment size distribution in the bed in Sibsa River. There are samples showing sand in the downstream end, while further upstream the samples are consistently cohesive.

The bed samples from the Pussur River show a consistent sandy channel center in the newly processed bed samples collected from all available sources (several IWM bed samples). The Pussur bed seems to be influenced by Gorai, which makes sense when considering the direct connection from Pussur to Gorai. However, the connection from Sibsa to Gorai is less direct than to Pussur.

The best we can do for the Sibsa River model is to use the bed samples, which do not show a consistent pattern, but they do show dominating cohesive sediment.

The bed samples from the Sibsa River indicates negligible quantities of sand; hence no sand fraction is required in the Siba River model.

4.4.1 Alternative 2-fraction sediment model including sand and silt

Previous bed samples suggest that the Sibsa River is sandy downstream and cohesive upstream, the latter confirmed by the new bed samples, while no new bed samples were collected downstream. The most characteristic feature of the Sibsa River compared to the Pussur River is that Sibsa is essentially a dead river end with very low net flow during the monsoon, while Pussur has a much higher net flow during the monsoon. It is often seen that estuaries with small net sand transport exhibit strong spatial grain size variations, as we also see in some of the old Sibsa bed samples.

The large bar in the downstream end of Sibsa is not well captured in the model, e.g. the transverse bed slope for the bar is poorly descibed. If the bar is sandy, the behaviour will be very different from what is simulated.

We explored a 2-fraction model, but it was deemed too subjective due to the lack of data. Especially the lack of bed samples and particle size distribution data for Akram Point are problematic.

4.5 Sediment transport boundary conditions

All boundaries use constant sediment concentrations in the Sibsa model:

- Upstream concentration: 200 g/m^3
- Side channels: 200 g/m^3
- Downstream: 200 g/m^3

A C(Q) curve was developed at Akram Point for the Pussur River, but it was not used in the Pussur model nor in the Sibsa model. The downstream concentration is also not very important, so a constant concentration is sufficient.

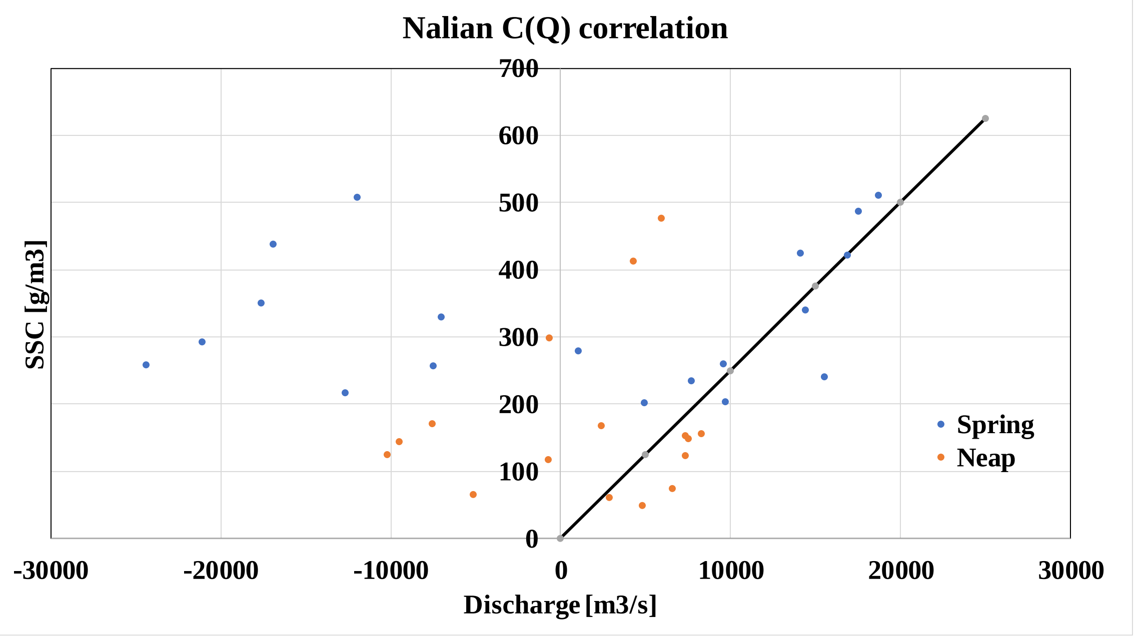


Figure 4-11 C(Q) curve for Nalian in Sibsa River based on the 2016 data.

Figure 4-11 shows a C(Q) correlation for the Nalian suspended sediment data. The data for ebb conditions (positive flow) shows a very good correlation between discharge and concentration, which is also what would be expected if the sediment load from upstream is influenced by entrainment. The correlation for flood conditions is not as strong but still shows increased concentration with increased discharge. Again, this suggests that the signal is influenced by entrainment and not just boundary conditions.

Tests were conducted using the Nalian correlation (straight line in the figure) for ebb conditions, while no upstream boundary condition is used in the advection-dispersion for flood conditions. We found that the results were similar to the results obtained by using constant 200 g/m^3 upstream.

4.6 Sediment transport calibration

The cohesive sediment is modelled using the traditional cohesive sediment erosion (E) and deposition (D) functions, see Mehta et al (1989). The model was calibrated with the following parameters:

$E_0 = 0.015$ g/m^2/s

$\tau_{ce} = 0.2$ N/m^2

$\tau_{cd} = 0.1$ N/m^2

$w_s = 1$ mm/s

n=1

porosity = 0.6

Initially, the parameters were adjusted to match concentrations and then refined by matching bathymetry developments. This means that the calibration of the sediment parameters was really an iterative process, which we document in two separate sections. Hence, the parameters reported in this section are influenced (heavily) by the subsequent section describing the calibration to bed level changes.

4.6.1 Sediment concentration validation for 2016

The 2016 validation is reported in this section.

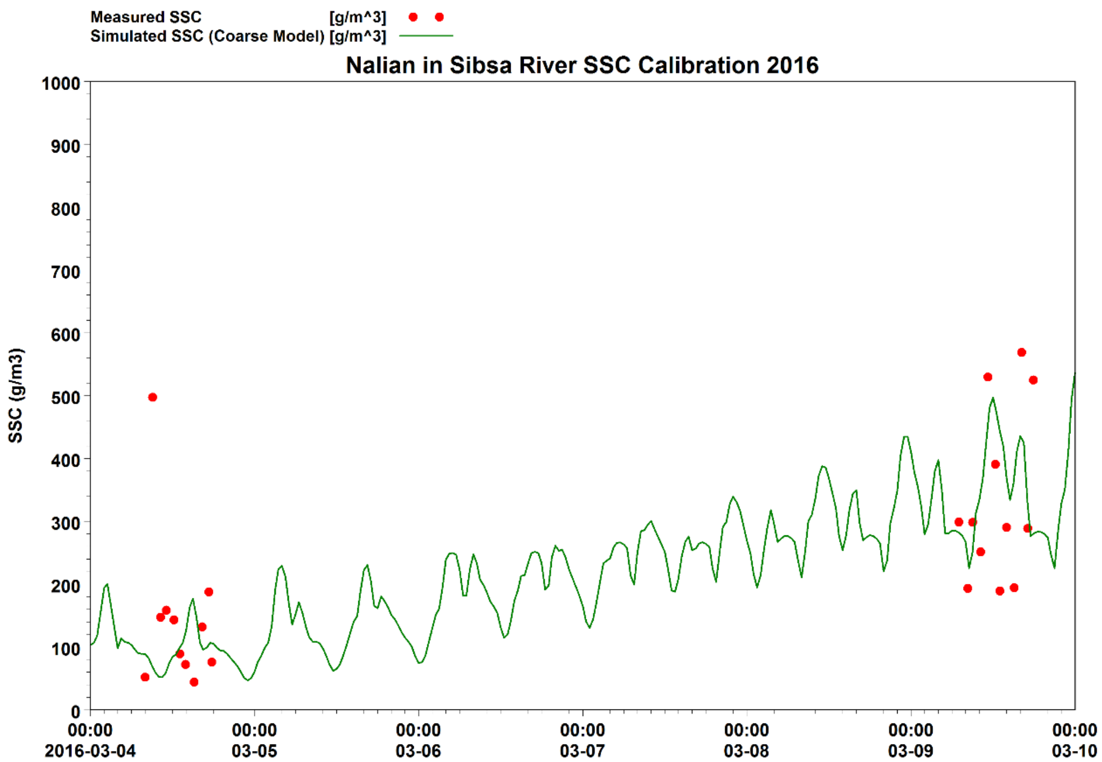


Figure 4-12 Calibration of SSC at Nalian in Sibsa River during 2016.

The Nalian station suspended sediment concentration data was used for the initial adjustment of the cohesive erosion and deposition functions. It must be stressed that Nalian is very close to the upstream boundary, so the simulated concentrations at Nalian for ebb flow conditions are influenced by the upstream boundary condition, which is not the same for flood conditions.

4.7 Validation against observed bed level changes 2011-2019

The best way to calibrate and validate morphological models is to hindcast the morphological development. One thing is to get correct concentrations, another thing is to get correct bed level changes, and the ultimate is to get both right.

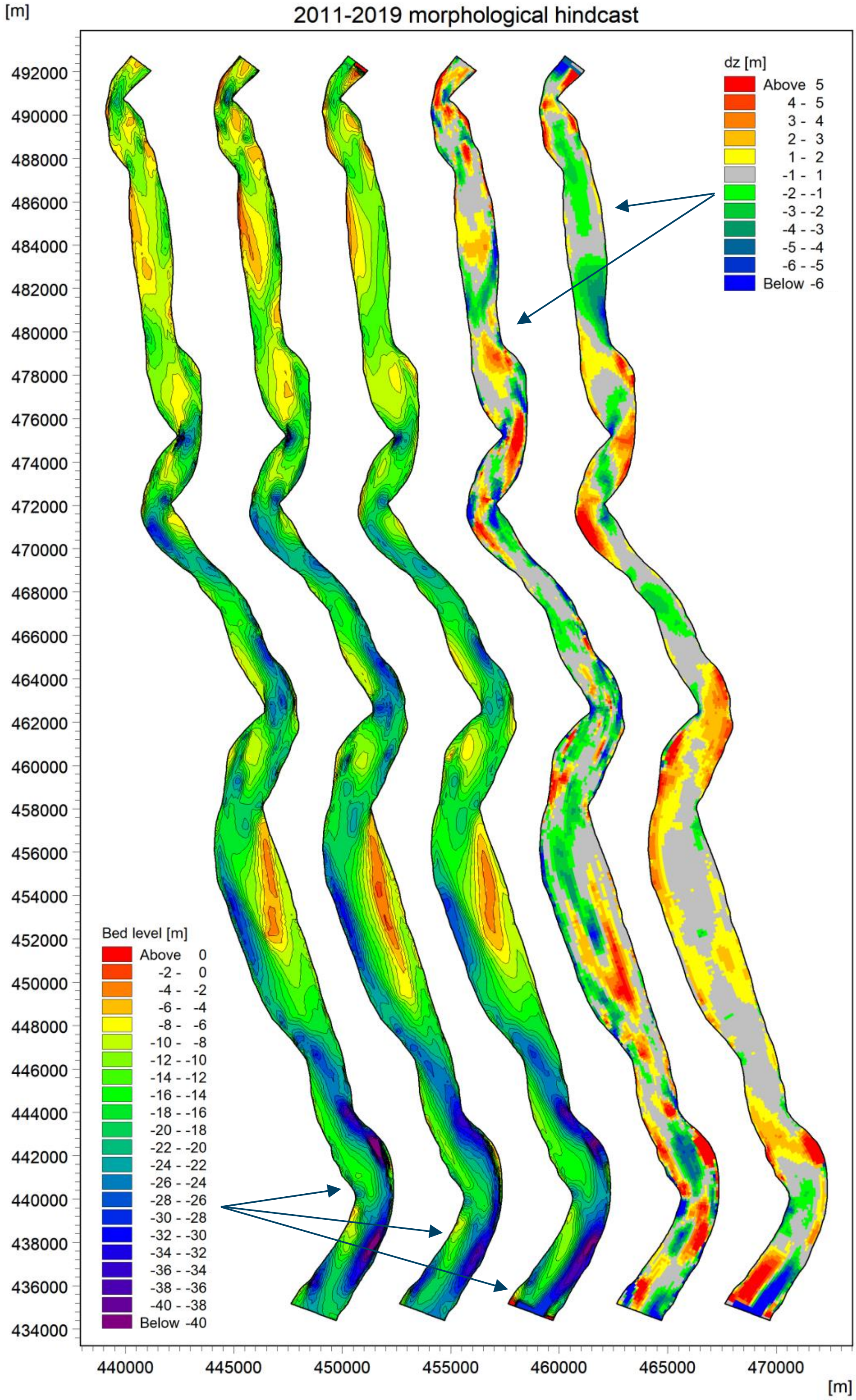


Figure 4-13 Comparison of observed and simulated bathymetry development 2011-2019, from left: Observed bathymetry 2011, Observed bathymetry 2019, Simulated bathymetry 2019, Observed bed level changes 2011-2019, Simulated bed level changes 2011-2019 (R206).

Figure 4-13 shows the observed and simulated bathymetry developments in the hindcast period 2011-2019.

Note: R206 is our internal reference for the hindcast simulation adopted as model calibration. We add this reference to the report to ensure consistency in the model application, i.e. ensure that the model applications are based on the correct hindcast.

4.8 Validation against observed bulk volume curves

The spatial bed levels and bed level changes are very useful for showing the model calibration. Another way to compare is to use volume curves, which are calculated by width-integrating the bed level changes to obtain:

- Width-averaged bed level change as a function of chainage
- Accumulated bulk volume curve showing the deposition upstream of the considered chainage

The volumes are calculated from bed level changes and are hence bulk volumes.

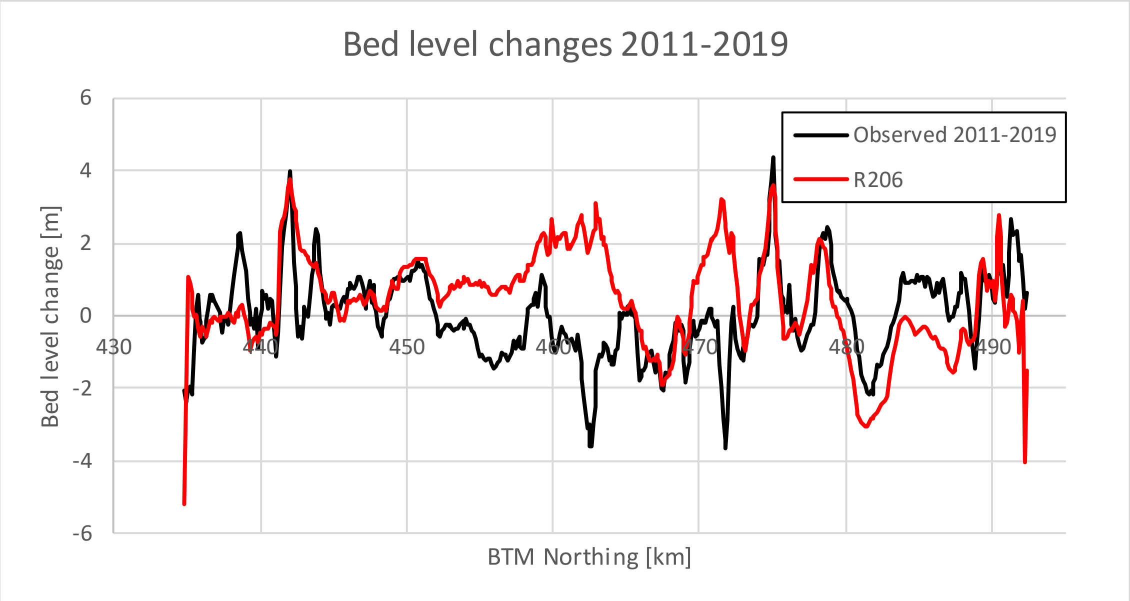


Figure 4-14 Comparison of observed and simulated width-integrated bed level changes 2011-2019 (R206).

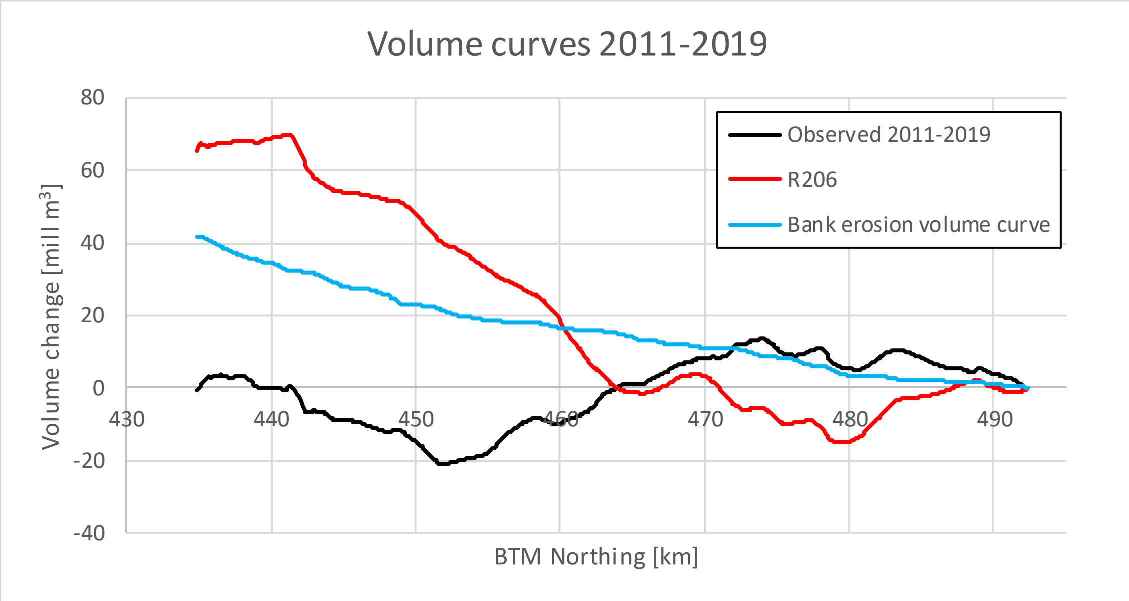


Figure 4-15 Comparison of observed and simulated bulk volume curves for 2011-2019 (R206).

The curves for the calibrated model are shown in Figure 4-14 and Figure 4-15:

- For the Sibsa River model it is recommended to look at the local bed level changes, while the accumulated curves are not that useful; the accumulated curve is better when a model is consistently erosional or depositional (DHI and IWM, 2020a and 2020b).
- The local bed levels changes compare quite well to the observations in the upstream and downstream ends, while there are discrepancies in the central reach of the river
- Bank erosion contributes significantly to the sediment budget.

The major errors in the hindcast results are found in the central part of the model where the model predicts sedimentation and the observations show erosion. This makes the integrated volume curve in Figure 4-15 look not at all convincing, while the local bed level changes curve in Figure 4-14 looks convincing upstream and downstream, but not in the middle. We can also observe that the local bed level changes in general have the correct shape when comparing observations and simulations, with the exception in the middle of the model.

We note the following uncertainty: The Akram Point discharge is underpredicted by the model. If the Akram Point discharge stems from floodplain flow, it can at least on paper explain why we see deposition around 460 km, while the observations show erosion (returning floodplain flow). The returning floodplain flow can also explain why the deposition seems to want to move downstream compared the central part of the model.

4.9 Bank erosion model

The bank erosion model was adjusted with the following derived Hasegawa (1989) parameters:

- h_c = 10 m
- Eh = 10^{-6}

These are the standard parameters in our derived Hasegawa bank erosion formula.

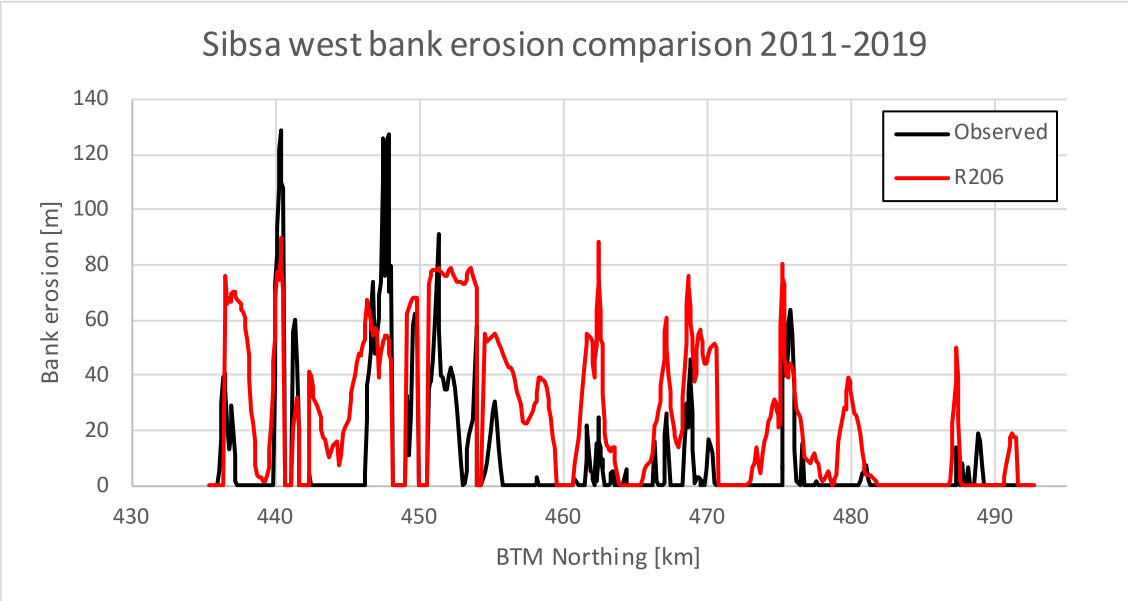


Figure 4-16 Calibrated bank erosion along west bank (R206).

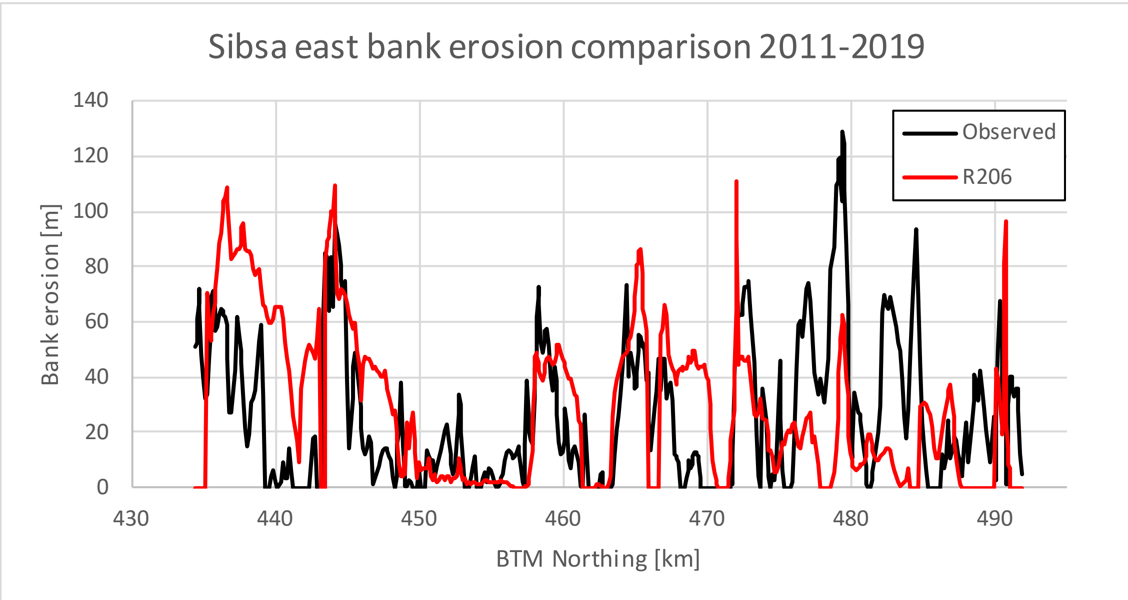


Figure 4-17 Calibrated bank erosion along east bank (R206).

Note: R206 is our internal reference for the simulation ID.

The observed and simulated bank erosion 2011-2019 along the east and west banks are compared in Figure 4-16 and Figure 4-17.

4.10 Comparison of observed and simulated bank lines 2011-2019

The bank erosion hindcast simulation was conducted without updating the bank lines. This is easier for calibration purposes because updating of the bank lines will change the j-coordinate locations along the banks, so direct comparison to observations cannot be done. The error associated with not updating the bank lines is small for cases where the bank erosion is much smaller than the width, which is the case for the Sibsa River 2011-2019.

Bank lines are difficult to show graphically, so we show detailed developments.

Note: R213 is our internal reference for the simulation ID.

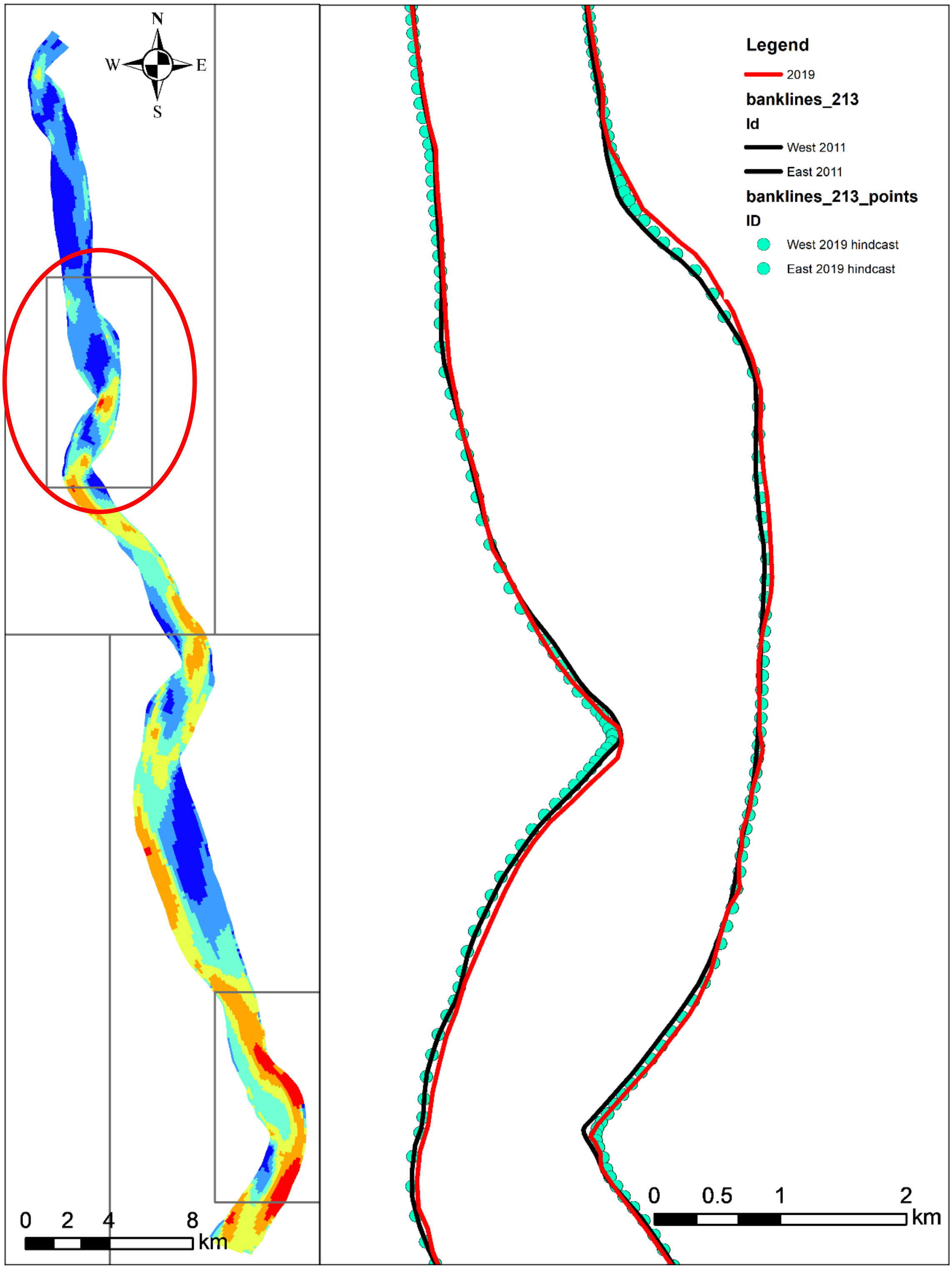


Figure 4-18 Comparison of observed and simulated bank lines in a local area in the upstream end (R213).

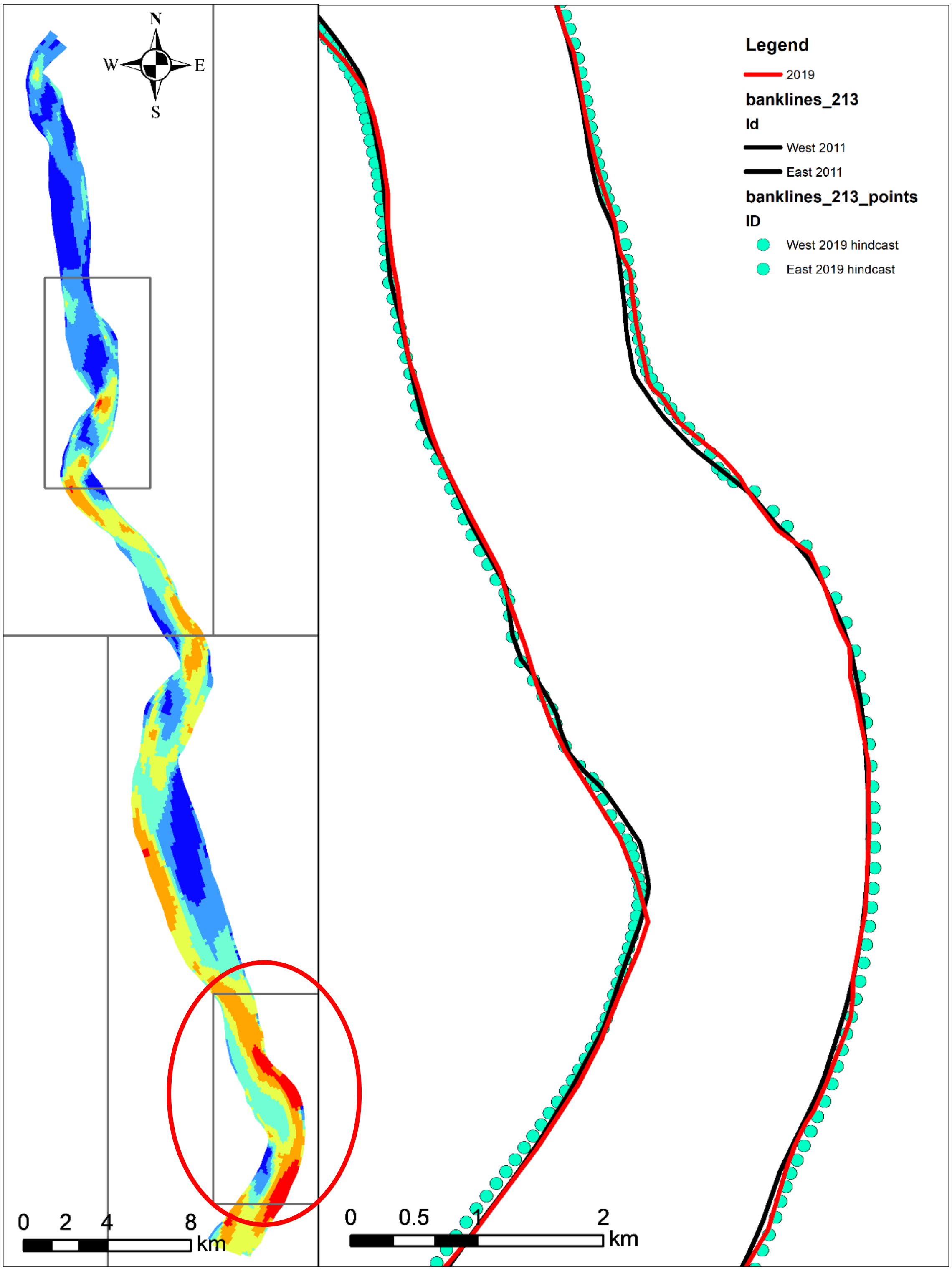


Figure 4-19 Comparison of observed and simulated bank lines in a local area in the downstream end (R213).

Local bank line details are shown in Figure 4-18 and Figure 4-19. These represent the actual bank line movements corresponding to the bank erosion as a function of northing coordinate.

5 Conclusions

The present report documents the development of the Sibsa River model developed using MIKE 21C.

Several historical bathymetry datasets are available for the Sibsa River. However, we only considered the two most recent datasets in the 2D model, as the previous datasets do not have enough resolution for 2D contouring. The two most recent datasets are from 2011 and 2019, and they even have almost identical resolution, which means we have an excellent basis for hindcasting 2011-2019 for model calibration.

Hydrometric data in the shape of water levels and discharges was used for calibrating the hydrodynamic model.

Several bed samples processed into particle size distribution were available. However, some old bed samples were only available as d_{50}-values. Those bed samples are very important because they show sand in the downstream end, but without the actual size distribution it is difficult to use these in the model. Even with the old bed samples available, the data coverage is still insufficient for the development of a 2-fraction sediment model. There is no doubt that the Sibsa River has a sediment regime locally characterized by a mix of sand and silt, but we do not have a clear picture of how this works.

Suspended sediment samples have only been collected at the Nalian station in the Sibsa River, while there is no suspended sediment data available at Akram Point. Sibsa also has particle size distribution data for the suspended sediment, which is very unusual. The particle size distribution data is, however, only available for ebb/flood slack conditions but shows that the suspended sediment has generally much lower fall velocities (stronger effect for slack conditions) compared to the bed samples. The lack of concentration data and associated particle size distribution data at Akram Point is a shortcoming in a river that could be morphologically influenced by sand in the downstream end. Without the Akram Point suspended sediment data, including particle size distribution, we cannot determine the sediment transport in the downstream end, which is important for the morphological behaviour, especially for the sand import to the river from the downstream estuary.

Bank erosion was processed from Landsat images 1988-2019. The historical bank lines show very consistent and systematic bank erosion for the whole period. For the vast majority of banks along the Sibsa River we observe that bank lines, which were eroding in 1988, also eroded in 2019, and the annual bank erosion rates are similar for the banks, both spatially and temporally. The bank lines were processed into erosion as a function of northing along the west and east banks, and we demonstrate that bank erosion correlates extremely well with bed levels in the way that essentially all eroding banks have deep water and are located in outer bends. The sediment volumes associated with bank erosion are significant compared to volumes associated with bed levels. The period 2011-2019 showed almost neutral sediment behaviour, i.e. only internal movement, while the bank erosion contribution was significant compared to these transported volumes.

A curvilinear grid was generated for the Sibsa River with 500x20 grid points. The 2011 bathymetry data was contoured on this grid. A separate 2019 grid was developed from the 2019 bank lines with the 2019 bathymetry interpolated.

Hydrodynamic boundary conditions were provided by IWM from the SWRM for the period 2011-2019 (30 min time-step). The boundary conditions consisted of upstream discharge, several side channels and downstream water level time-series. Of particular interest for the Sibsa River is that the upstream end has a very low net flow during the monsoon (zero net flow during the dry season), which means the Sibsa is almost a dead end. This suggests that the Sibsa River should be a longitudinal sediment sorter with cohesive sediment upstream and sand downstream (imported from downstream), which is consistent with the bed samples.

The hydrodynamic model calibration and validation show that the Sibsa River model consistently underpredicts discharges at the downstream Akram Point. We have not attempted to solve this problem, as it is inherited with the boundary conditions from the SWRM. We have analysed the problem and concluded that the upstream Nalian discharges appear to be correct, so either the local floodplain exchange is underpredicted or the SWRM does not correctly capture the known complex interaction between the Sibsa and the Pussur rivers. This shortcoming could also influence the simulated morphological behaviour in the downstream end.

The sediment model was formulated as a silt model with a representative fall velocity of 1 mm/s. This was based on the bed samples, while the fall velocities for the suspended sediments based on the suspended samples are an order of magnitude lower. This means that we will have difficulties calibrating the silt model to both bed levels and sediment concentrations, and therefore we emphasize the bed levels, which are far more important than the sediment concentrations.

We explored the alternative use of a 2-fraction sand and silt model, which is implied by the bed samples and the hydraulics (upstream dead end). However, this was very problematic due to the lack of bed samples and suspended sediment concentrations at Akram Point.

The cornerstone of the morphological calibration is a morphological hindcast 2011-2019. For the Sibsa River this can be conducted with reasonable reproduction of bed level changes in the period, even when suffering from uncertainties in the data and model inputs. The model also calibrates well to observed sediment concentrations at Nalian, although this was de-emphasized in the model development because we deemed that bed level changes were more important than sediment concentrations.

The Sibsa River model calibrates extremely well in the upstream end, while in the downstream end the model calibration is not satisfactory. We can tie this discrepancy to the probably sandy bed in the downstream end, lack of Akram Point concentration data and the consistent underprediction of discharges at Akram Point.

Of particular interest in the downstream end is what looks like a large sand bar poorly described in the silt model. If the downstream sediment is sandy, the bar behaviour would be very different. In the silt model description, the bar does not exhibit a behaviour suggesting significant transverse sediment transport, which we would expect in a sand formulation.

Bank erosion was simulated using almost the same formula used for other rivers in the project. Bank erosion hindcasting 2011-2019 showed good agreement with the observations, with the correct banks eroding and the magnitude correctly reproduced. However, bank erosion in the Sibsa River does not correlate as strongly with the bed levels as we have seen in other rivers. Bank erosion in Sibsa appears to be a messier signal than e.g. in the Pussur River.

5.1 Recommended future data collection

The Sibsa River model has been developed, but some improvements can be added:

- Data collection aimed at improving the Akram Point discharge is essential for improving our understanding. The Akram Point discharge improvement needs to start in the SWRM, which provides the boundary conditions to MIKE 21C.
- There are too few bed samples available in the Sibsa River to describe the spatial distribution of sand and silt. Many more samples should be collected, both longitudinal and transverse and on various morphological features (bars, channels, islands etc).
- ADCP data should be measured in riverbends to improve our understanding of the velocity distributions. Traditionally IWM do not collect ADCP data in bends, but this should be done, and the data should be processed into velocity profiles and not just discharges.

- Suspended sediment concentrations and particle size distribution data should be collected at Akram point. At present no observations are available.
- Bank material samples, including particle sizes and porosities, should be collected for the Sibsa River. At present no observations are available.

The data listed above is traditionally not collected in Bangladesh.

5.2 Recommended model improvements

The largest shortcoming in the model lies in the lack of ability to correctly predict bed level changes in the downstream end. Improvements in this area require more data. We are confident that the model performance can be significantly improved with a 2-fraction sediment description provided there is sufficient data to construct such a model.

6 References

DHI and IWM (2020a). *MIKE 21C Pussur meso-scale bank erosion morphological modelling study: Model development report*. CEIP-1, Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics).

DHI and IWM (2020b). *MIKE 21C Baleswar meso-scale bank erosion morphological modelling study: Model development report*. CEIP-1, Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics).

Hasegawa, K. (1989). *Universal bank erosion coefficient for meandering rivers*. Journal of Hydraulic Engineering, 115(6), 744-765.

Mehta, A. J., Hayter, E. J., Parker, W. R., Krone, R. B., & Teeter, A. M. (1989). *Cohesive sediment transport.* I: Process description. Journal of Hydraulic Engineering, 115(8), 1076-1093.