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)

Bishkhali River: Meso scale bank erosion modelling - current situation & future projections

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

May 2022

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Coastal Embankment Improvement Project, Phase-I (CEIP-I)
Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone
Office: Flat #3/B, House #4, Road #23/A, Banani, Dhaka 1213, BANGLADESH Phone +880 1307 693299

Memo No: CEIP/LTMRA/0622/172 5 June 2022

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

Attn: Mr. Syed Hasan Imam, Project Director

Dear Mr Imam,

Subject: Submission of the Bishkhali River: Meso Scale Bank Erosion Modelling – current situation and future projections (D-4A-2:1,2&3)

It is our pleasure to submit herewith five copies of the Report Titled ***"Bishkhali River: Meso Scale Bank Erosion Modelling – Current situation & future projections".*** According to the World Bank Tracker, this report falls under component ***D-4A-2:1,2&3.***

This report includes both model development and applications. The model development report titled "Meso scale bank erosion modelling – current situation – interim report" was submitted earlier and was reviewed by the World Bank. DHI revised the interim report to address the review and extended to include future projections.

There are five chapters in this report. Chapter 1 is the introduction chapter describing the background, objective and approach. Chapter 2 gives an overview on the availability of measurement data and how the data was processed. The development and calibration/validation of the model are described in Chapter 3. Model applications are documented in chapter 4, while the report finalizes with conclusions in Chapter 5.

Thanking you,

Yours sincerely,

Dr Ranjit Galappatti
Team Leader

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

CONTENTS

FIGURES

TABLES

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
EHRM	Eastern Hilly Regional Model
FAP	Flood Action Plan
FM	Flexible Mesh
FFWC	Flood Forecasting and Warning Centre
GBM	Ganges Brahmaputra Meghna
GCM	General Circulation Model
GIS	Geographical Information System

GRRP	Gorai River Restoration Project
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
MIKE 11	DHI’s 1-dimensional hydraulic model
MIKE 21C	DHI’s 2-dimensional model made specifically for river morphology
MIKE FM	DHI’s 2-dimensional flexible mesh flow model
MoWR	Ministry of Water Resources
MPA	Mongla Port Authority
MSL	Mean Sea Level
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
SWMC	Surface Water Modelling Centre
SWRM	South West Region Model

TBM	Temporary Bench Mark
TRM	Tidal River Management
ToR	Terms of Reference
UTM	Universal Transverse Mercator
WARPO	Water Resources Planning Organization
WL	Water Level

EXECUTIVE SUMMARY

DHI and IWM studied five rivers in the coastal zone of Bangladesh as part of the project "Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)".

This Executive Summary applies to all meso-scale bank erosion models and reports developed during the study. The same Executive Summary can be found in all five model reports.

The main objectives of the modelling study were to develop predictive bank erosion tools for selected rivers and to estimate future bank line changes under different scenarios.

The five rivers were studied with emphasis on meso-scale bank erosion, and the rivers listed from west to east are: Sibsa, Pussur, Baleswar, Bishkhali and Sangu. The four rivers in the SW region of Bangladesh are all tidally dominated, while the Sangu in morphological terms is dominated by the monsoon hydrograph.

One report was issued for each of the studied rivers. The same overall modelling approach was used for all five rivers, and therefore all the reports followed the same template.

The overall approach can be summarized into:

- 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, calibration, and validation of the model with field measurements and remote sensing data
- Morphological hindcast – reproduce historical bathymetric and bank line shifting
- Scenario runs - study future changes in the morphological processes based on possible scenarios, e.g. climate change, upstream development and subsidence
- Output - geospatial datasets of present erosion and sedimentation in the river system for various seasons and for possible scenarios

The following data were required for each model:

- Bathymetries
- Hydrometric data (water levels and discharges)
- Sediment bed samples
- Sediment bank material samples
- Suspended sediment concentrations
- Suspended sediment particle size distributions
- Historical bank lines from satellite imagery

All meso-scale bank erosion reports follow this template:

- Introduction
- Data
- Model development
- Model application
- Conclusions

Bank erosion

Bank erosion patterns in Bangladesh vary significantly from the monsoon dominated fluvial rivers to the tidally dominated muddy rivers. Two main reasons were identified in the study:

Firstly, tidal flow: The monsoon dominated rivers exhibit large imbalances between the dry season and monsoon, while the tidally dominated rivers do not show this imbalance, but instead exhibit similar discharge amplitudes during the dry season and monsoon. Due to this, the monsoon dominated rivers will experience very high morphological activity during the monsoon, which will be followed by high bank erosion rates, while the tidal rivers are better adjusted morphologically to the hydraulic conditions all year. In practice, monsoon dominated rivers are morphologically inactive during the dry season.

Secondly, cohesion: The tidally dominated rivers have cohesive banks, which are erosion resistant, while the sandy banks in most inland fluvial rivers have much higher erodibility.

The difference between fluvial and tidal rivers is significant and can also be followed along the coastal zone with strong tidal dominance in the west and monsoon dominance in the east. The increase in erosion from west to east can even be followed gradually from the Baleswar to the Bishkhali and increases further in the Sangu River.

Bank erosion rates in the tidally dominated muddy rivers are typically 5-10 m/year, while the rivers are kilometres wide, hence annual erosion is less than 1% of the width. Further to the east, bank erosion increased markedly in the Bishkhali and increases dramatically in the Lower Meghna and Sangu when measured relatively to the width (the absolute erosion rates in Lower Meghna are measured in hundreds of meters per year, while Sangu is narrow).

The value of Landsat data in Bangladesh
In most countries, Landsat data (30 m satellite imagery) is of little use for determining bank line movements due to the lack of resolution in the images compared to bank erosion rates. However, in Bangladesh, Landsat imagery is extremely useful because bank erosion rates are high. Although annual bank erosion cannot be followed in the tidal rivers from Landsat images, bank erosion over 5-10 years can be tracked accurately in the Landsat imagery. The Landsat data hence became a prism through which bank erosion in the past could be identified accurately.

The relatively slow bank erosion in the tidally dominated rivers was also found through data analysis to be systematic, such that a bank eroding in 1988 is extremely likely also to be eroding in 2019, and more or less with the same rate.

Model development template
The model development followed this template:

- Select model extent
- Develop curvilinear grid
- Interpolate bathymetry data to the curvilinear grid
- Extract hydrometric boundary conditions from e.g. the South West Regional Model (SWRM)
- Develop sediment transport boundary conditions
- Calibrate hydrodynamic model to observed water levels
- Calibrate sediment transport and morphological model to observed bed level changes
- Calibrate bank erosion model to observed bank line changes

The models were developed as hydro-morphological models with bank erosion included and physically moving the curvilinear grids to account for bank line changes. Model calibration was performed in depth by using the period 2011-2019 as hindcast, which was found ideal due to the two bathymetry datasets typically collected in 2011 and 2019 by IWM with almost identical resolution and accuracy. The value of such data cannot be overstated, and by combining with bank erosion obtained from Landsat data in the same period, the models could be calibrated in depth. There are exceptions to this, namely that no 2011 bathymetry was available for Bishkhali River, while Sangu River was calibrated to 2018-2020 for which good data was available.

The calibration of the tidally dominated rivers resulted in very similar calibration parameters, especially the silt transport models and bank erosion formulas were almost identical in the rivers.

Bank erosion mechanics and formula

The bank erosion formula is central to the simulated behaviour of the rivers. Several bank erosion descriptions were investigated in detail in the models, and the optimal choice was found to be a formula derived from Hasegawa (1989). The Hasegawa model is based on a near-bank excess velocity approach, which means that bank erosion occurs when the near-bank flow speed is higher than the cross-section average flow speed. This could in principle have been adopted in the model engine, but it was found to give some practical problems because the Hasegawa formula was developed for meandering rivers with an outer bend and associated bend scour, which is not always the layout for the tidal rivers. Hence, the formula was modified by estimating the excess flow speed from the near-bank flow speed and an estimated average flow depth using the Manning formula. This resulted in bank erosion derived from the near-bank flow speed and water depth, notably bank erosion is proportional to the near-bank flow speed and a function of the water depth, such that the water depth must exceed a characteristic average depth for bank erosion to occur and then it will increase with depth beyond this limit.

Several bank erosion expressions were found calibratable to observed bank erosion, even with significant variations in the described mechanics. The best calibration was obtained by simply using a critical bank height (Mosselman, 1995) beyond which bank erosion increases with the exceedance of the bank height beyond the critical height. However, this was found mechanistically problematic because it does not state anything about erosive fluid forces along the bank, and hence bank erosion would continue along any bank independent of the flow along the bank, if the bank height exceeded the critical limit.

Bank erosion calibration using the Hasegawa derived formula is only slightly less accurate than for the critical height formulation, and Hasegawa has a solid theoretical foundation in addition to its inclusion of the flow speed along the bank. Hence, all taken into consideration, there was no doubt that Hasegawa was the correct choice.

Several traditional bank erosion descriptions were tested without success. For instance, a simple bank erosion description is to derive bank erosion from near-bank scouring; however, this does not work in the tidal rivers because the description is only valid for sandy banks. Surprisingly, relating the bank erosion rate to the shear stress was initially found to give a bad description of bank erosion. This was also the case when relating bank erosion rate to the flow speed without considering water depth.

It is important to understand that in addition to being able to describe the bank line changes over time, the bank erosion formula also needs to describe the physical processes in a lumped manner. The adopted Hasegawa derived formula derives bank erosion from flow speed and water depth, which proved to be the two most important variables.

Limitations in the models and data

In general, the models developed suffer from similar limitations, which are also related to the lack of specific types of data. The limitations are listed in the order of importance.

In particular, all models show that simulated bar formation is sensitive to flow resistance used in the models and that the flow resistance calibrations adopted in the models are only one variant in a calibration space. Detailed investigations were conducted to show that different resistance models can be developed to yield the same simulated water levels but resulting in different velocity distributions between bars and channels as well as different sediment transport patterns and hence different bar sizes. Essentially the models have calibration spaces where the true calibration cannot be identified solely by matching water levels. Consequently, the bathymetry and bank erosion behaviours can vary significantly. The best approach for reducing calibration uncertainties is to collect ADCP velocity profiles, but this was not done as part of the present project.

The sensitivity of bar development to the flow resistance model used is very pronounced. For instance, a constant resistance number applied in a model can cause bars to erode in a manner where the deep channel will be located where the bar should be located and vice versa. In turn, this will lead to a simulated bank erosion where the erosion pattern essentially becomes the opposite of the observed. Due to feedback in the river morphology, this can also cause other bars to behave incorrectly. The implication of this sensitivity is that when the model simulates the right morphological development, this is a strong indication that the right resistance model has been applied.

The models also suffer from uncertainties in the calibration of sediment concentrations. This comes back to the traditional way of collecting data in Bangladesh, namely the standard collection of total sediment concentrations (i.e. the combined concentration of clay, silt and (fine) sand). The tidal rivers contain significant clay concentrations, which do not contribute morphologically. In the tidal rivers only the silt transport contributes to the morphological development since the sand concentration is negligible. Hence, it is not possible to calibrate silt transport models to the observed concentrations, as the observations generally only show the total concentration. However, observed particle size distribution data was available only in a few cases.

Only a handful of bank sediment samples were available. The erosion resistance of banks depends on the sediment composition of the banks. Bank erosion plays an important role in the river morphology, in some of the rivers contributing significantly to sedimentation, but the particle size distributions in the banks is largely unknown.

Rivers with mixed sediments require many bed samples to identify the particle size distribution in the riverbed. All the tidally dominated rivers are probably characterized by a mixture of sand and silt (while clay is morphologically inactive), but it was only possible for some of the rivers to identify this mixture, and none of the rivers had enough bed samples to determine the spatial distribution of the bed sediment composition.

The limitations of the available dataset have probably impacted the quality of the calibration of the models. However, the fact that the models all predict the overall morphology of the rivers quite well, including bank line migration and erosion/deposition pattern of the riverbeds, gives some confidence that also flow distribution, sediment transport etc. are well represented in the final model calibrations. Further model improvements can be made at a later stage if/when additional data collection is carried out. IWM has the capacity to conduct the necessary data collection.

<u>Model applications</u>
Model applications included the following:

- Projection of bank lines 30 years into the future
- Impact of climate change
- Impacts of bank protection on bank erosion and bed levels
- Dredging of shoals to mitigate or eliminate bank erosion
- Access to Mongla Port

Projection of bank lines 30 years into the future
The most important deliverable of the project was projected bank lines 30 years into the future for the four tidally dominated rivers in the west (Sibsa, Pussur, Baleswar and Bishkhali). The future projections showed that most of the banks currently eroding will continue eroding in the future with more or less the same rates. Hence, the future development was essentially projected to be similar to the 1988-2019 development. This is a very important finding that can be utilized for planning and managing polders and embankments. There are deviations from the overall systematic behaviour, but these are few in numbers. The projected future bank lines were also submitted to the CEIP-2 feasibility study in digital format (line themes) in order to maximize the value to planners and decision makers. Projection of bank erosion 30 years into the future is not meaningful for the Sangu River because the erosion rates are too high compared to the river width for projections on such timescale and was therefore not conducted.

Impact of climate change
In most of the models, climate change increases the tidal flow amplitude slightly, leading to a small increase in bank erosion. However, the impact of climate change is small compared to the absolute future bank line changes. Hence, the impact of climate change on future bank lines is modest.

Impacts of bank protection on bank erosion and bed levels
Bank protection was also shown to induce scouring due to the removal of sediment sources associated with bank erosion. The effect on bed levels is not insignificant, while bank erosion impacts are small. The models do not suggest that local bank protection will cause significant changes to the erosion of other banks, which is an important conclusion to keep in mind for management purposes, i.e. eroding banks do not seem to significantly influence each other in the tidal rivers.

Dredging of shoals to mitigate or eliminate bank erosion
The use of dredging of shoals located opposite of eroding banks was tested in the Baleswar River. The model results suggest that shoal dredging is potentially very effective at reducing bank erosion, especially if combined with backfilling of dredged spoils in the deep channel along the eroding bank. Unfortunately, this cannot be conducted simply by dumping the spoils in the deep channel due to the settling length for the silt exceeding the length of the eroding bank. However, the impact of shoals dredging combined with filling the deep channel essentially eliminates bank erosion over a long timescale and should be studied further, assuming that the filling problem can be addressed. A simple approach using geotextile (e.g. jute) bags to secure sedimentation in the deep channels was proposed, but needs to be investigated further and tested.

Access to Mongla Port
A separate investigation was also carried out for Mongla Port. Several scenarios were tested using the model, including quantification of the impact of Ganges Barrage, bank protection, closing and/or regulating upstream connections to Sibsa, guide bunds at Mongla, and TRM applied to Pussur or Sibsa. The investigation confirmed that the fundamental problem with Mongla Port is that the Sibsa incoming flood tide occupies (captures) most of the tidal prism located upstream of Mongla Port, preventing the incoming slower tide in the shallower Pussur River from occupying the tidal prism. The Pussur flood tide hence stagnates at Mongla Port, making the port susceptible to sedimentation, and model results show that Mongla Port indeed has the highest sedimentation rate in the Pussur River. The only way to really fix the sedimentation problem is to prevent the Sibsa from capturing tidal prism from the Pussur, while other schemes do not really solve the underlying problem, although they can act to mitigate. Schemes involving attempts to add tidal prism to the Pussur are remarkably ineffective due to the always faster flood tide in Sibsa, which will occupy tidal storage before Pussur. In effect adding tidal basins to Pussur downstream of Mongla Port just causes the Sibsa to capture more of the upstream tidal prism.

Conclusions

The conclusions from the study can be summarized into the following.

Bank erosion in the tidally dominated rivers of Bangladesh is slow and systematic, and therefore the predictability is very good, even over decades. This is a very important finding that can be utilized for planning and managing polders and embankments, for instance, designing embankments in safe distance from the eroding rivers, planning future retirement of embankments or when to implement bank erosion measures. On the contrary, fluvial systems in Bangladesh are known to have good predictability only over relatively short timescale, if even that.

The five developed models reflect the bank erosion predictability. For the four tidally dominated rivers, the bank erosion model was applied for projections 30 years into the future, while this is not meaningful for the Sangu River.

Although one should never take morphological predictions as accurate, the project team is confident that the future bank lines projected 30 years into the future are reliable enough for decision-making purposes. The predictable planform development should be exploited when managing polders and banks.

Dredging of shoals located opposite of eroding banks shows promising results, although only tested conceptually. The best outcome is achieved by combining dredging with dumping of the spoils into the deep channel flowing along the eroding bank, which will give two synergizing effects, namely attracting flow to the dredged flow path through the shoal and attracting less flow to the deep outer channel. There is a major practical issue with the approach, namely that it is not easy to dump the spoils into the outer channel. One proposal for handling this is to fill the spoils into geotextile bags and dump them in the outer channel, which is similar to the approach followed in some meandering rivers for navigation purposes (by preventing deep bend scour), but here done to prevent bank erosion (by also preventing deep bend scour).

For the Sangu and other fluvial systems, managing polders via predictable future bank lines is not meaningful. However, a river like the Sangu has a meander belt, which has good predictability, even if the bank lines themselves are difficult to predict. However, this may require allowing the Sangu River to move within its meander belt, which means accepting a loss of land area behind polders.

The model shows that Mongla Port has the highest sedimentation rate in the Pussur River model. In other words, Mongla Port happens to be located at the worst possible location for a port.

The Pussur River model was also applied to scenario testing at Mongla Port. The fundamental problem with Mongla Port is that it is located just south of the tidal meeting point between the Pussur and Sibsa tides, which has been understood for decades, and indeed some of the scenarios addressing this problem have been tested before. Several mitigation schemes were tested, and it was found that the most effective solution is to increase the Pussur tidal prism located upstream of Mongla Port. Getting the Pussur flood tide to flow north from Mongla can only be done by preventing the faster Sibsa flood tide from occupying the prism. Closing the three upstream connections to the Sibsa River was proposed and tested almost 30 years ago by DHI (1993), and the present study reverified the validity of this scheme. However, the scheme can be further developed by using regulators on the connection rivers to enhance the outgoing tide (ebb) at Monga Port, which is the driver for keeping the Mongla Port water depths sufficiently large. It was shown that closing the connections appears neutral in the Mongla Port bed levels, while significant scouring can be achieved with regulators, opening up for managing the Monga Port bathymetry by using the regulators to adjust the hydraulic dredging driven by the ebb flows.

The use of guide bunds at Mongla Port, proposed before, was investigated by using the MIKE 21C model. It was found that this scheme can sustain deep channels at Mongla Port, but it will also induce sedimentation further downstream due to the slightly reduced tidal discharges associated with the added flow resistance from the guide bunds. This suggests that the guide bund scheme cannot stand alone in solving the Mongla Port problem.

Various other schemes were also investigated, in particular increasing the tidal prism of the Pussur downstream of the tidal meeting point located upstream of Mongla Port. Schemes involving an increase in the Pussur tidal prism downstream of the tidal meeting point are problematic because they ultimately leave more tidal prism for the Sibsa flood tide to occupy from the Pussur upstream of Mongla Port.

A real solution to the Mongla Port problem must address the ability of the faster Sibsa flood tide to capture (from the Pussur) tidal prism upstream of Mongla Port, which is the fundamental problem. Mitigation schemes that do not address the fundamental problem do not seem to be able to stand alone.

1 Introduction

1.1 Background

Bangladesh is situated at the confluence of three great trans-Himalayan rivers, the Ganges, the Brahmaputra or Jamuna, and the Meghna, which form the Bengal (or GBM) Delta. While over 90 percent of the catchment of the GBM system lies outside of Bangladesh, more than 200 rivers and tributaries and distributaries of the GBM system drain through the country via a constantly changing network of channels, tidal inlets and creeks, forming the most active large delta on the planet. The coastal land mass is shaped by the interaction of large volumes of sediment laden water with the moderate to high tides of the Bay of Bengal.

Land in the coastal zone is built up by the deposition of river sediments in the tidal delta, including the mangroves of the Sundarbans, the largest mangrove forest in the world. The deposits of sand, silt, clay, and organic material form the land mass which, despite subsidence due to continuous consolidation of layers many kilometres deep, is kept around the level of the highest tides by the continuing deposition of sediments.

The coastal zone of Bangladesh spans over 710 km of coastline and is subject to multiple threats. Sixty-two percent of the coastal land has an elevation less than 3 meters above mean see level. With a sediment supply of 1 billion tons per year, this is the delta with the largest sediment supply in the world. This leads to continuing accretion of the land area in the coastal zone (5-10 km^2/year), mainly in the Meghna Estuary, but also erosion of the coast farther west. It has been observed that the land subsidence rate may vary from place to place due to anthropogenic factors such as drainage and ground water extraction as well as the properties and depth of underlying strata. On top of this there are tectonic plate movements, particularly in the eastern delta, that give rise to other changes in ground level.

The coastal lands, particularly in SW Bangladesh, being subject to regular flooding by saline water during high tides, could not be used for normal agricultural production in a country with a very high demand for land. The Coastal Embankment Project (CEP) was initiated in the 1950s and 1960s to build polders surrounded by embankments preventing the spilling of saline water onto the land at high tides. These embankments were built along the larger rivers and across the smaller rivers and creeks which then formed the drainage system within each polder and connected to the peripheral rivers via appropriately sized flap gate regulators, that open at low tide to let the drainage water out.

The Coastal Embankment Project enabled the reclamation of large tracts of land for agriculture from 1960 onwards. Polder building proceeded continuously until today. Up till now, 1.2 million hectares have been reclaimed in 139 active polders in the coastal zone of Bangladesh.

In over half a century of its existence, a number of challenges have surfaced that threaten the long-term safety and even the very existence of the polder system as a viable and sustainable resource. These are:

- Sea level rise and changes in precipitation and water discharge due to climate change
- Threats of damming and diversion to the delivery of river sediments from upstream
- Subsidence of lands (except where it has been allowed to be rebuilt by tidal flooding) and structures founded on existing land
- Drainage congestion due to accumulation of silt in some peripheral waterways around polders
- Changes in tidal hydrodynamics and related river erosion and siltation in the peripheral rivers of polders
- Increasing vulnerability to cyclones and storm surges

The main objective of the “Long-term monitoring, research and analysis of 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 field and modelling work within the project is carried out to improve understanding of the long-term and large-scale dynamics of the Ganges-Brahmaputra-Meghna (GBM) delta. There is insufficient knowledge about sediment budget in the delta involving sediment transport within the estuaries, sediment sources and sediment distribution into the river system. Sediment and tidal dynamics are important for river and coastal erosion, land reclamation, and delta development. Subsidence of the land alters the topography and hydrodynamics and increases flooding, coastal erosion and salinization. The knowledge of sediment dynamics, distribution, subsidence, erosion-deposition processes, 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 is essential for the framework of polder design.

In the coastal zone of Bangladesh – both in the major estuaries and in the peripheral rivers of the polders – bank erosion is a significant problem even though the erosion rates are normally smaller than those encountered further upstream in the non-tidal main rivers (e.g. Padma, Brahmaputra). Failure of embankments in the coastal zone during storms has not always been as the result of overtopping. There have been many failures as a result of undermining of the toes of the embankment due to riverbank erosion. In fact, unexpectedly high levels of bank erosion have already been encountered in the execution of CEIP-1. This matter was highlighted in the Inception Workshop of this project leading to the recommendation that a special meso-scale study of “Bank Erosion Hindcasting” should be undertaken to analyse the bank erosion processes that have taken place in the large tidal estuaries in the last 20 or more years in areas where large and often intensive data collection programmes have been mounted for various projects. Improved guidelines for predicting medium term bank erosion are supposed to emerge from this study.

Figure 1-1 Revetment along Baleswar River (photo 11 February 2019).

1.2 Objective and Approach

The main objective of the modelling presented in this report is to develop a predictive bank erosion tool for the Pussur River and to estimate future bank line changes under different scenarios.

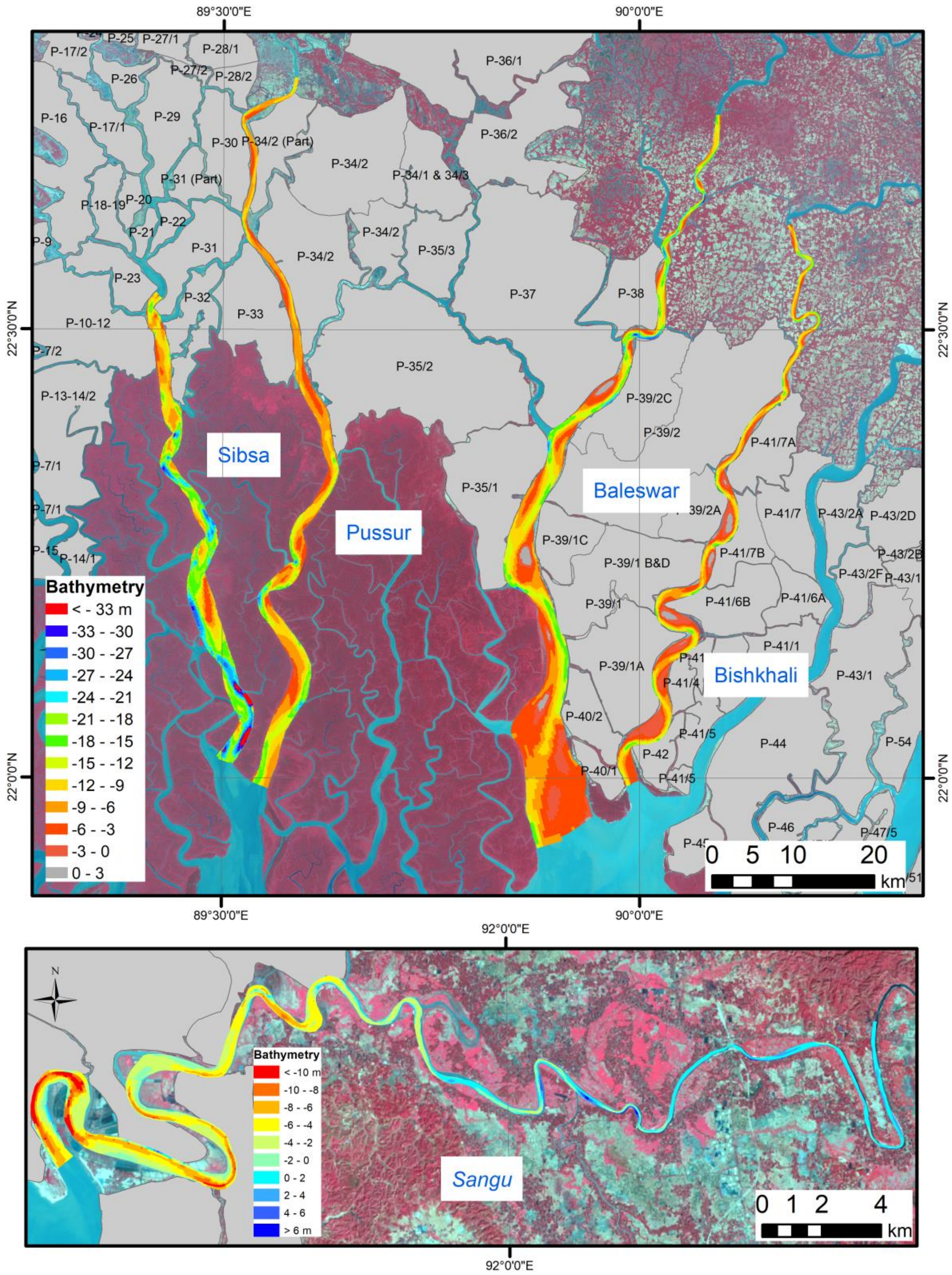

Figure 1-2 The five MIKE 21C models developed for the project.

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, calibration, and validation of the model with field measurements and remote sensing data
- Morphological hindcast – reproduce historical bathymetric and bank line shifting
- Scenario runs - study future changes in the morphological processes based on possible scenarios, e.g. climate change, upstream development and subsidence
- 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

The modelling is carried out using MIKE 21C. The key features of this modelling system are:

- Curvilinear boundary conforming grids allowing accurate representation of the river planform with relatively few grid points
- 2D Saint-Venant equations with a parallelized and optimized solver allowing time-true simulations covering several years
- Helical flow
- Multi-fraction sediment framework covering mixtures of clay, silt, sand, gravel
- Bed-load calculated with inclusion of helical flow and bed slope
- Suspended load calculated from advection-dispersion with helical flow included
- Morphological updating of the bed levels
- N-layer substrate model
- Bank erosion with optional inclusion of eroded material in the sediment budget
- Dynamic updating of the curvilinear grid to account for bank line changes

Waves are not included in any of the MIKE 21C models. The fetch is generally small within the estuaries of the delta, and the modelled rivers are very deep, usually at least 10 m and often up to 40 m water depth along eroding banks, which means that the small surface waves will not penetrate to the lower water column, hence it may be assumed that waves have little influence on the sediment transport in the areas modelled.

1.3 This report

An interim report describing the model development for the current situation was submitted earlier in the study and reviewed by the World Bank. The interim report was titled:

“Meso scale bank erosion modelling - current situation - interim report”

DHI revised the interim report to address the review, and the report was extended to include future projections. The final report was titled:

“Meso scale bank erosion modelling – current situation & future projections”

The interim report is included already in the final report and not submitted separately.

The five modelling reports are organised in a similar manner with the following chapters: Chapter 2 gives an overview on the availability of measurement data, as well as how the data was processed. These data are used in Chapter 3, which describes the development and calibration/validation of the model used to study the river morphology and bank erosion. Model applications are documented in Chapter 4, while the report finalizes with conclusions in Chapter 5.

1.4 General definitions

It is useful to provide some general definitions and explanations for the terminology used in this report.

The projection is always BTM, and the vertical datum is always mPWD. In some cases, data was made available in UTM and MSL, but they were converted.

All MIKE 21C models were developed with the grid direction going in the direction of the river from upstream. This means that the discharge sign convention is that ebb flow is positive and flood flow is negative in all models.

The term “mud” is defined as a mixture of mainly fine-grained sediments, organic matter and water where the cohesive properties of the clay fraction, enhanced by the properties of the organic matter, dominate the overall behaviour of the sediment mixture.

Several figures present results in ways that can seem confusing if the reader is not aware:

- Some figures show Bishkhali River divided into upstream and downstream
- Some figures show several Bishkhali River maps side-by-side

The MIKE 21C models are very long, and to avoid narrow graphics, the 2D figures are made by splitting the river into upstream and downstream parts shown side by side, with the upstream part to the left and the downstream part to the right. Grids and bathymetries are shown in this manner.

The plots with several Bishkhali 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 as well as bed level changes shown together with the bathymetries. 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. When showing more 2D variations together in this manner, there can be several colour scales in a figure, and the reader is notified in the caption.

For one-dimensional variations, it is necessary to introduce a chainage coordinate. Although the river runs generally north to south, the northing cannot be used as a unique coordinate along the river. The chainage coordinate was calculated along the grid centreline of the river, starting from 0 at the upstream end, and these chainages do not align to the SWRM. All one-dimensional variations are shown as functions of this chainage.

1.5 Important note regarding MIKE 21C version

The developed MIKE 21C models take advantage of the most recent developments of the modelling software, hence it is important that MIKE 21C version 2022.1 or later is used. This version is installed on the project computers.

2 Data

This section documents all the data that was used for the model development.

The projection is BTM, and the vertical datum is mPWD.

2.1 Bathymetry

A very limited bathymetry survey was conducted in 2009, while for the present project a detailed bathymetry was collected in 2019. Unfortunately, no bathymetry survey was conducted in 2011 for Bishkkhali River, which means that the model cannot be calibrated accurately to bed level changes using 2011-2019 hindcasting. Hence, the bathymetry survey conducted as part of the present project is the first bathymetry survey conducted for Bishkhali River with sufficient detail for 2D contouring.

Table 2-1 Bathymetry data for Bishkhali River. The 2019 survey has a spatial resolution with cross-sections typically spaced 1 km longitudinally and with 10 m spacing across the river, while the 2009 bathymetry has too sparse cross-sections to allow 2D contouring.

Bathymetry data collection year	Sources
2009 (dates not available)	IWM (FFWC)
2019 (28/3-31/3)	Primary data (present project)

The available bathymetry data is shown in Table 2-1, while the contoured bathymetries are shown in Figure 2-1. Because there is only one contoured bathymetry (2019), bed level changes over a period are not known for Bishkhali River.

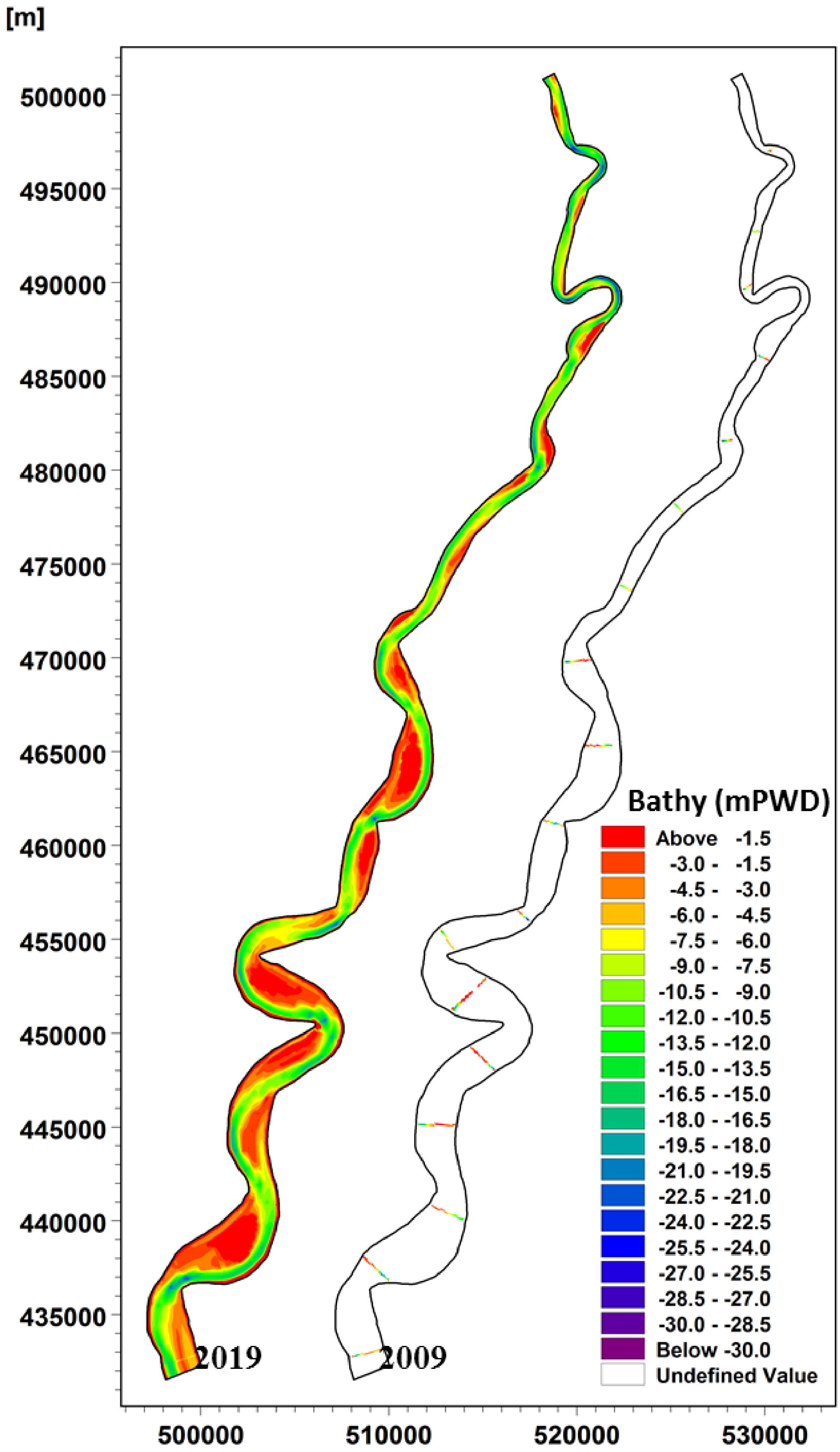

Figure 2-1 Bathymetries 2009 (right) and 2019 (left) for Bishkhali River. The 2009 data was too sparse to make meaningful contours that could be compared to the other years. Due to only one contoured dataset, bed level changes could not be calculated.

2.1.1 Analysis of 2009 and 2019 cross-sections

The bathymetry data from 2009 and 2019 were difficult to compare in a 2D model because the 2009 data was too sparse to make meaningful 2D contours. However, the 2009 data was still valuable for understanding the morphological changes, if interpreted appropriately. In such a case, the lowest resolution should dictate the approach when comparing the data. The cross-sections were already available in MIKE 11 format in the SWRM.

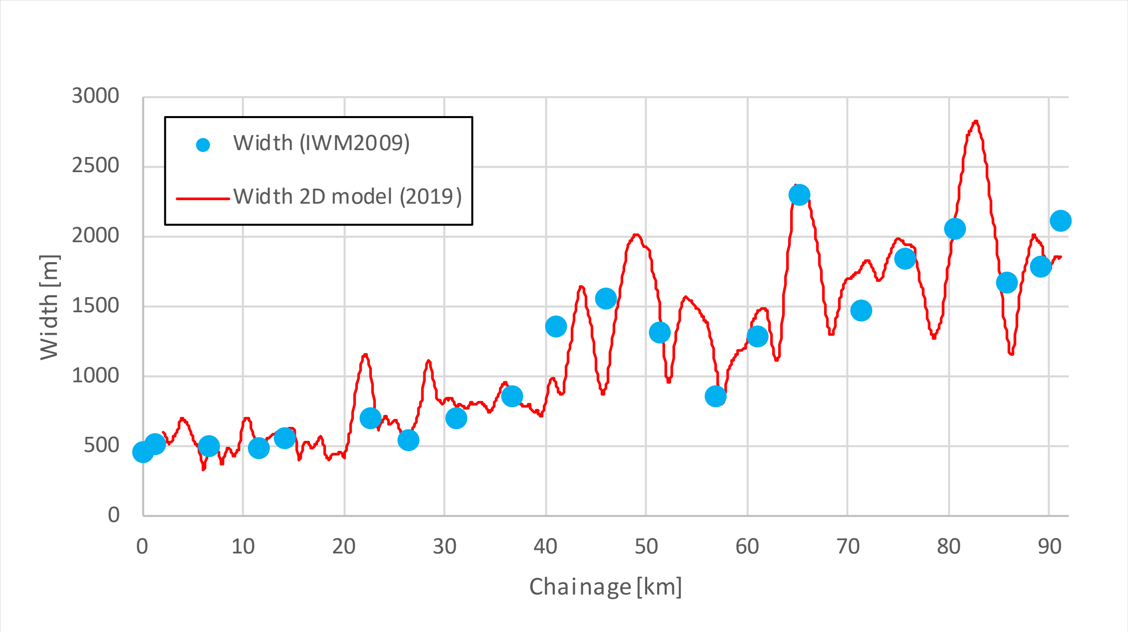

Figure 2-2 Width check of the 2009 and 2019 bathymetry data; this is done to ensure that there are no chainage displacements in the models. The width is most suited for verification due to its characteristic shape changing slowly over time.

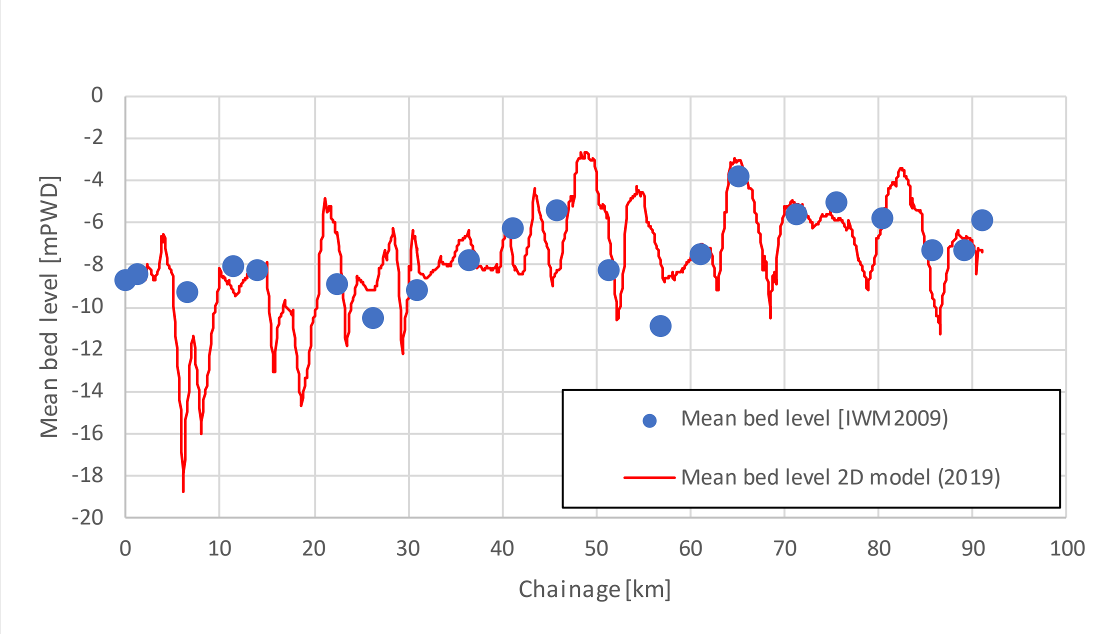

Figure 2-3 Mean bed levels from the 2009 cross-sections and the 2019 MIKE 21C bathymetry.

To ensure that the 2009 cross-sections and 2019 2D bathymetry align, the channel widths were processed separately from the cross-sections and grid, as shown in Figure 2-2. The distance along the channel in the 2D model was calculated from the grid centre line, and a constant was added to the chainages to improve the alignment to the 1D chainages. This resulted in the upstream 2D model boundary being located at chainage 2 km. The figure shows that the widths align reasonably, but there are deviations, which could not be fixed with a constant added to the 2D chainage.

The mean bed levels from 2009 and 2019 are shown in Figure 2-3.

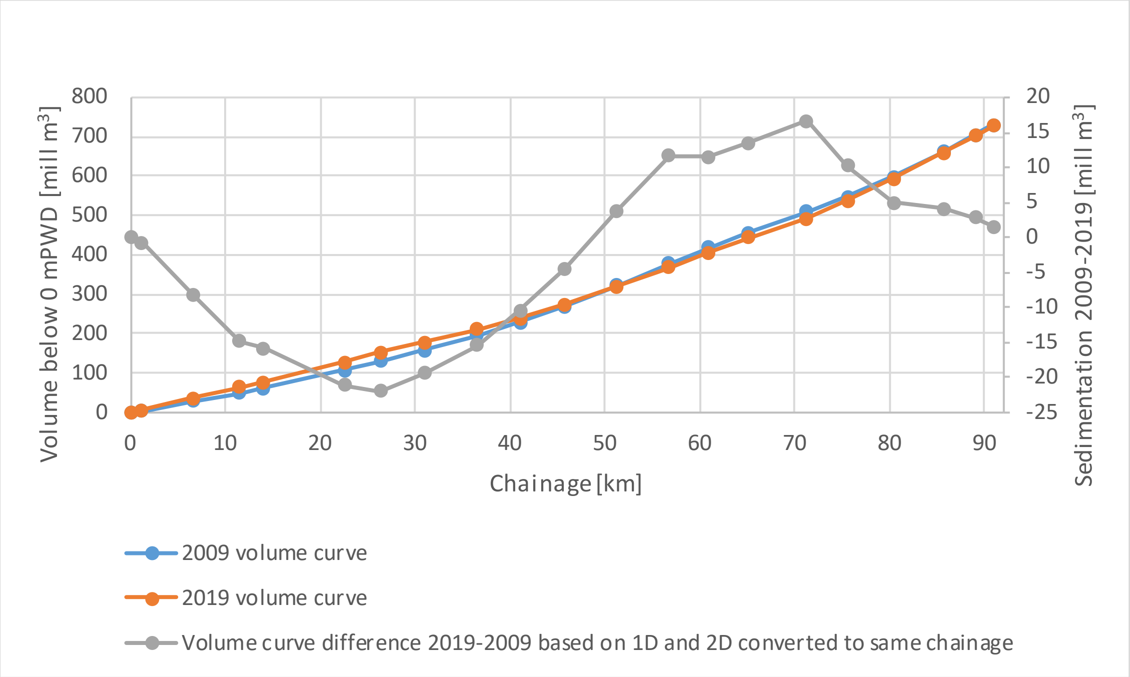

Figure 2-4 Estimated sedimentation (bulk volume curve) from 2009 to 2019. The 2D model bathymetry from 2019 was processed to flow areas, which were converted to the 2009 chainages, and both volume curves (below 0 mPWD) were calculated, followed by calculation of the sedimentation curve.

The bulk volume curves are difficult to compare due to the different resolution in 2009 and 2019, so the datasets were converted to the 2009 resolution, as shown in Figure 2-4:

- The 2009 cross-sections define the 2009 area below 0 mPWD curve
- The 2D bathymetry from 2019 was processed into flow areas below 0 mPWD
- The 2019 flow areas were interpolated to the same chainage as 2009
- Volume curves were integrated for both years (same axis)
- The difference curve is then the sedimentation

It is seen that overall, 2009-2019 was neutral (no sedimentation over the model length), while erosion is observed upstream (2-25 km), sedimentation in the middle (25-72 km) and erosion downstream (72-92 km).

The “observed” sedimentation curve is only used for illustration in the model development. The curve is too uncertain to be used with full confidence. The purpose of the analysis is to provide some means for evaluating the simulated bed level changes to observations, which cannot be done directly in Bishkhal River because only one (2019) bathymetry with high enough resolution is available.

2.2 Hydrometric time-series

Hydrometric data include water levels and discharges.

Observations of water levels are available at numerous stations in Bangladesh from two primary sources, viz Bangladesh Water Development Boards (BWDB) and Bangladesh Inland Water Transportation Authority (BIWTA). In this study, water level data collected by IWM was used in combination with simulated water levels from the South West Regional Model.

Water level data is available for Patharghata and Taltoli, while discharge data is available for Fuljuri and Kakchira. The stations are shown in Figure 2-5 while datasets details are in Table 2-2 and Table 2-3. 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.

Water level and discharges data collected as part of the project during 2019 were not used in the model development process, as the data were not available at the time when the model was developed.

Table 2-2 Measured water level data for Bishkhali River.

Water level collection period	Station Name	Sources
2015 (dates not known)	Patharghata (Bishkhali)	IWM (CEIP-1 Project)
2019 (15/2-28/7)	Taltoli	Primary data (present project)

Table 2-3 Measured discharge data for Bishkhali River.

Discharge collection year	Station Name	Sources
2016 (7 and 18 April)	Fuljuri	IWM (CEIP-1 Project)
2019 (10 March and 21 July)	Kakchira	Primary data (present project)

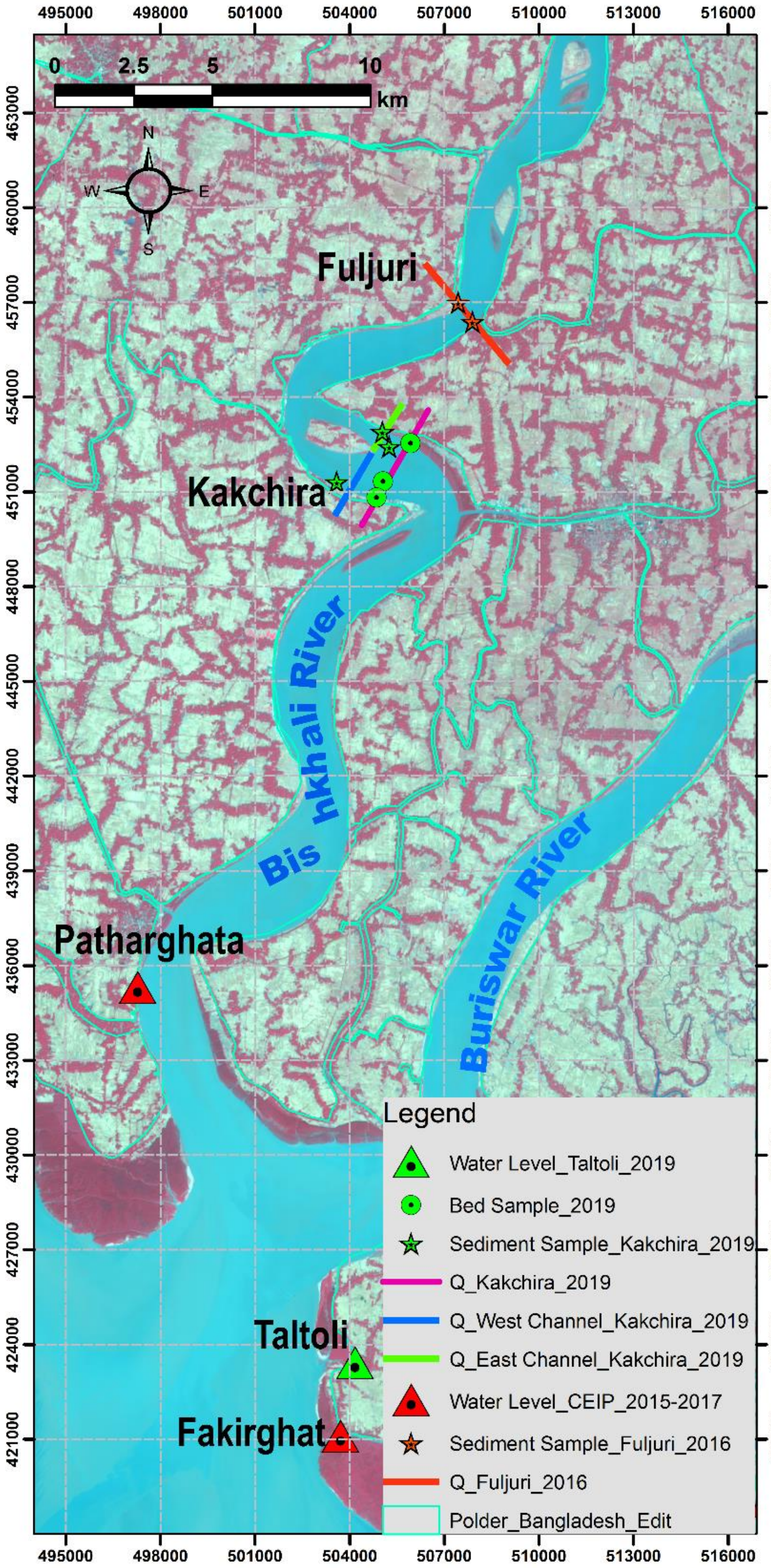

Figure 2-5 Field data collection map for 2015, 2016 and 2019 in Bishkhali River.

2.3 Sediment bed samples

Three bed samples were available from one cross-section in the Bishkhali River. The bed samples were collected in 2019 as part of the present project, and the locations are shown in Figure 2-7.

Table 2-4 Bed samples data from the Bishkhali River collected in 2019 as part of the present project. The Krumbein (1934) scale for size classes has been used, i.e. VFS = very fine sand, FS = fine sand, MS = medium sand. Note that the samples left and right (LB and RB) are not from the riverbank, but from the riverbed close to the bank.

BTM X [m]	**BTM Y [m]**	**Year**	**Name**	**Clay <0.005 mm [%]**	**Silt <0.063 mm [%]**	**VFS <0.125 mm [%]**	**FS <0.25 mm [%]**	**MS >0.5 mm [%]**
505932	452542	2019	Bishkhali_LB	7.37	89.66	1.49	0.97	0.50
505063	451329	2019	Bishkhali_CL	0.00	4.04	46.76	45.47	3.72
504853	450824	2019	Bishkhali_RB	4.08	50.57	15.40	26.76	3.19

Table 2-4 shows the bed samples processed into the Krumbein (1934) scale for the sand partition and clay/silt for the cohesive partition. The corresponding particle size distribution curves are shown in Figure 2-6. The bed samples were used for establishing the sediment model sediment sizes and fractions.

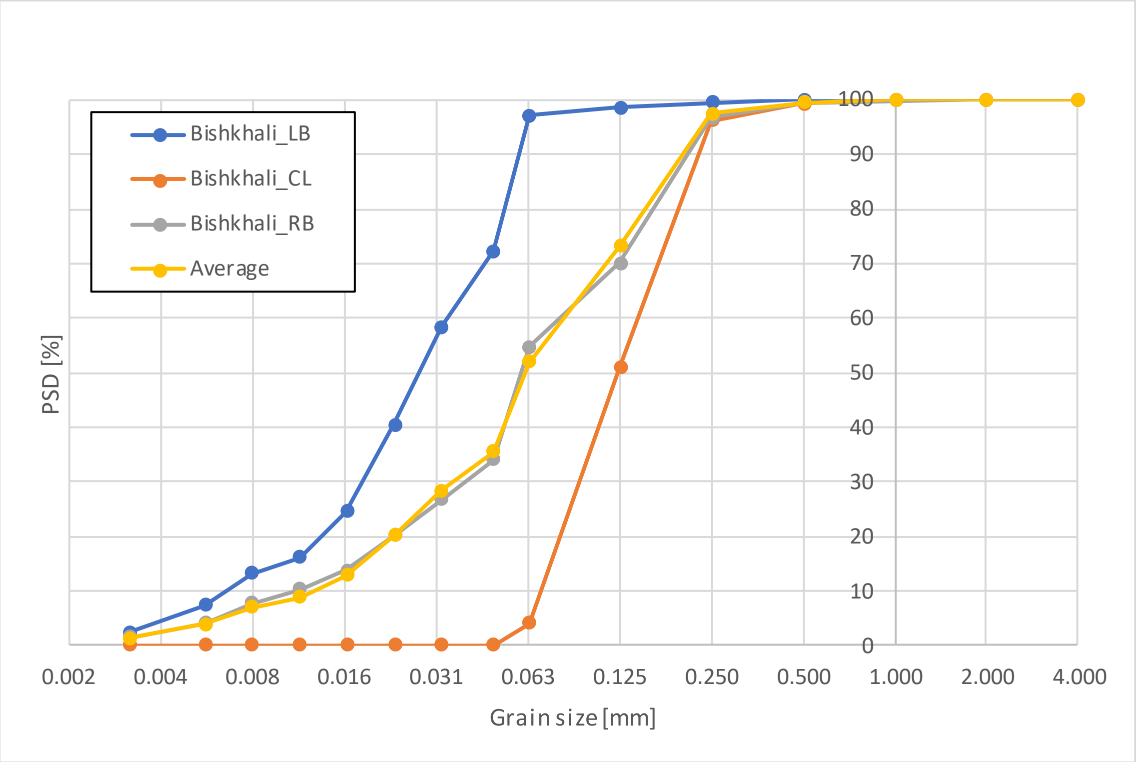

Figure 2-6 Particle size distribution of bed sediment in the Bishkhali River for 2019.

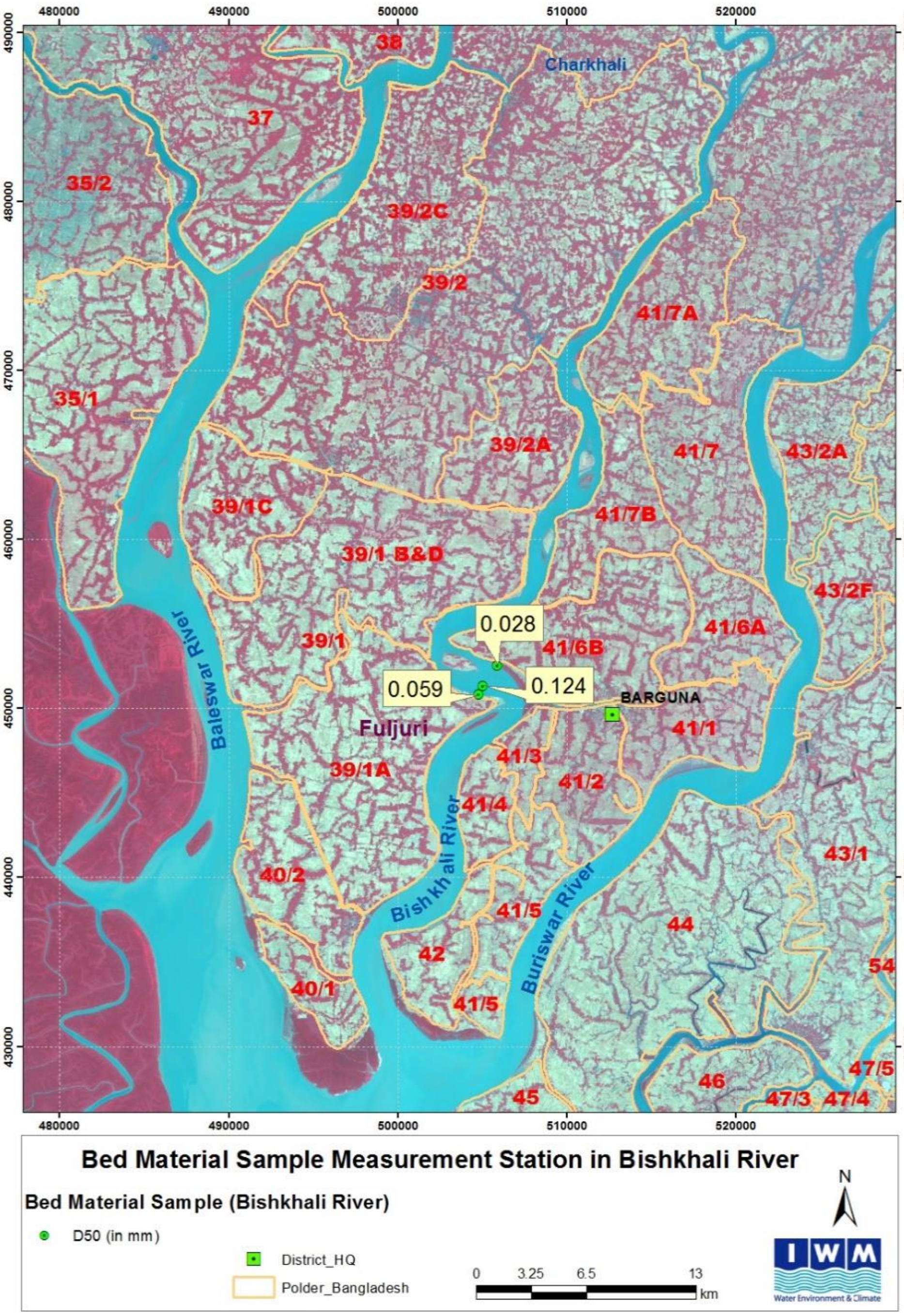

Figure 2-7 Bed samples d_{50} with locations during 2019 for the present project.

Closer inspection of the samples and bathymetry shows that:

- RB is located close to the bank in the main flow channel
- CL is located on the side slope of a large bar extending from the channel centre to the left bank
- LB is located close to the bank on the same large bar

The CL sample is sandy, which conforms to the experience from Pussur River with more samples available, while the LB sample is far away from the main flow and hence is almost purely cohesive. The sample in the main flow channel (RB) is mixed sand/mud. These observations are consistent with a mixed sediment regime and also similar to the pattern in Pussur River derived from a much larger number of bed samples.

2.4 Suspended sediment data

Suspended sediment concentration data was collected in 2016 at Fuljuri. Data was also collected during 2019 for the present project at Kakchira. The data was typically collected at the same time as the ADCP data was collected, also varying over time. The raw data contains concentrations at three levels: 0.2, 0.6, 0.8 times the depth and in some cases also 0.5 m above the riverbed. The data was processed into depth-integrated concentrations for use in the model development.

Table 2-5 Suspended sediment concentration data for Bishkhali River.

Year	Station Name	Sources
2016	Fuljuri	CEIP-1 project
2019	Kakchira	Primary data (present project)

The suspended sediment samples are summarised in Table 2-5, while the locations of the two stations are shown in Figure 2-5. In the following, the C(Q) correlations (discharge versus sediment concentration) are presented for Fuljuri (2016) and Kakchira (2019), which are sufficiently close to be shown in the same graph. This is a common approach in fluvial systems where it is used to establish a sediment transport rating curve. In fluvial systems, flows and sediment transport will be slowly varying, and there will generally be a relation between discharge, water level and bed shear stress, so also a unique sediment rating curve. This in contrast to a tidal system as the present, which means that a unique relation between discharge and sediment concentration cannot be expected. The plots, however, are useful for developing an understanding of the sediment dynamics and to generate continuous sediment concentration time-series to be used at the model boundaries.

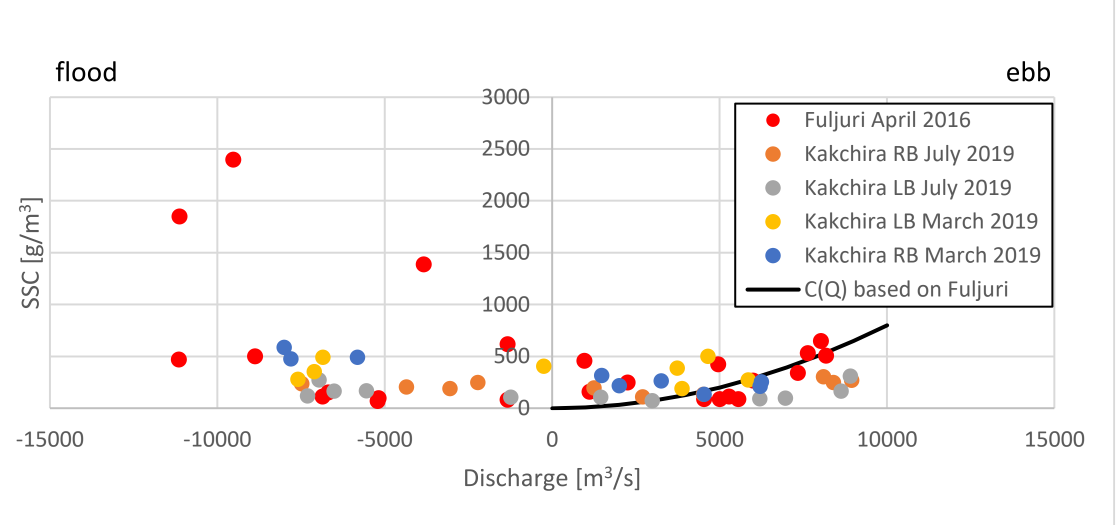

Figure 2-8 C(Q) correlations for Fuljuri (2016) and Kakchira (2019). It is noted that the three very high concentrations at Fuljuri appear in a noisy time-series where the concentrations jump up and down from 500 g/m^3 to 1500-2500 g/m^3 between individual measurements.

The resulting C(Q) correlation is shown in Figure 2-8. It is observed that for ebb flow, there is some increase in concentration with increasing discharge, but the correlation is not very strong. For flood conditions three separate observations in April 2016 (Fuljuri) show high concentrations, while the rest of the flood conditions observations show the same weak correlation between flow and concentration, which is seen also for ebb flow. No data was available for the particle size distribution of the suspended sediment.

2.5 Historical bank lines from satellite imagery

Historical bank lines were studied based on satellite images. To this end 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. The acquired images cover all the rivers in the coastal zone for which meso-scale modelling is carried out in this project, thus also the Bishkhali River. All the images are from the dry season from November to February as there were no cloud-free images during other seasons.

Bank lines were digitized from the images from 1988, 1995, 2001, 2011, and 2019 and are shown in Figure 2-9. In this figure, 25 locations with consistent and significantly eroding banks are indicated. It is observed that nearly all the locations with eroding banks are located along outer bends where the water depth adjacent to the bank is large (ebb channels). In addition, some eroding banks (see banks 19 and 20 shown in the figure) can be explained from smaller channels located between the bars and the inner bank (flood channels).

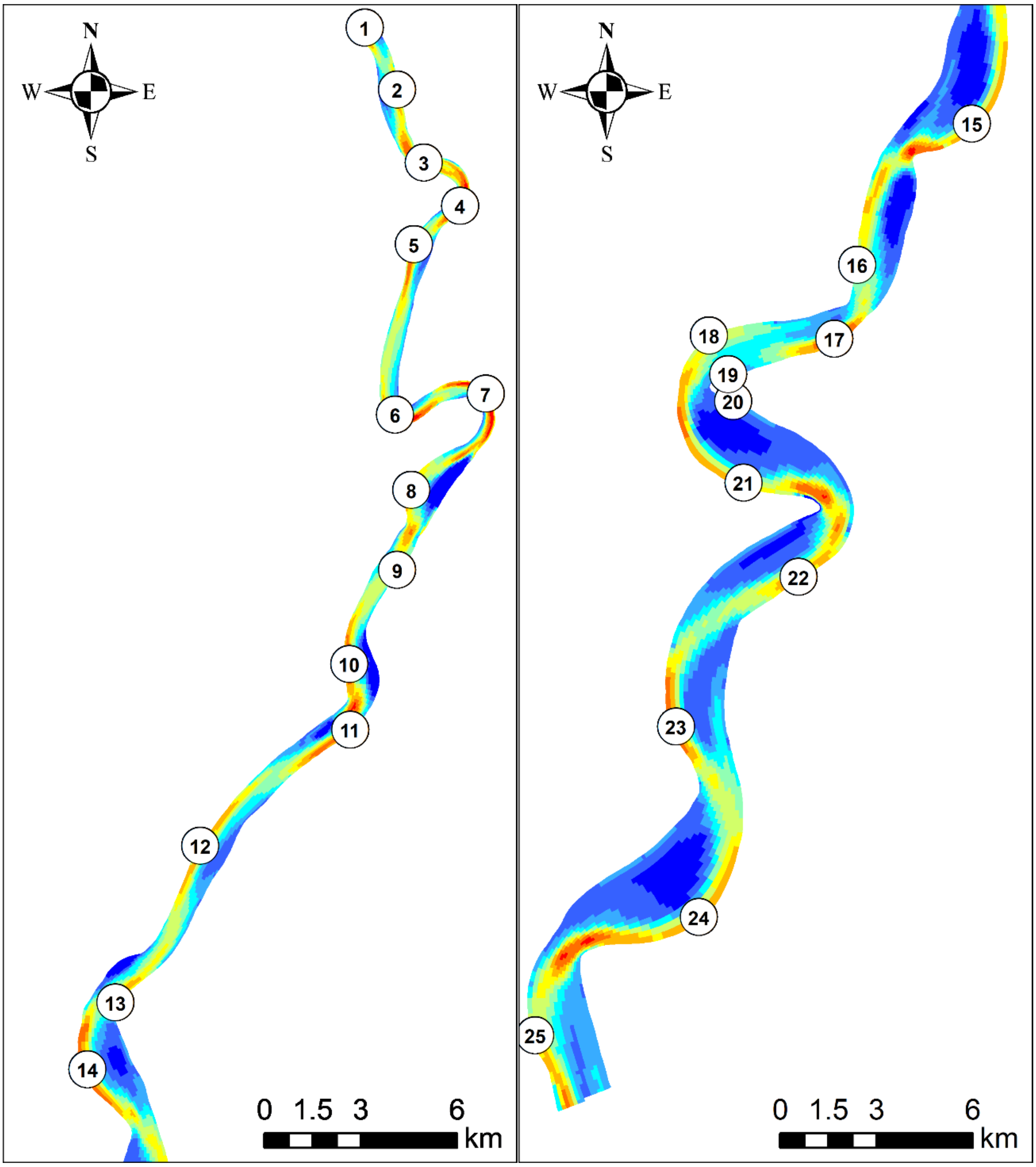

Figure 2-9 Bathymetry (2019) and eroding banks numbered 1-25 along Bishkhali River.

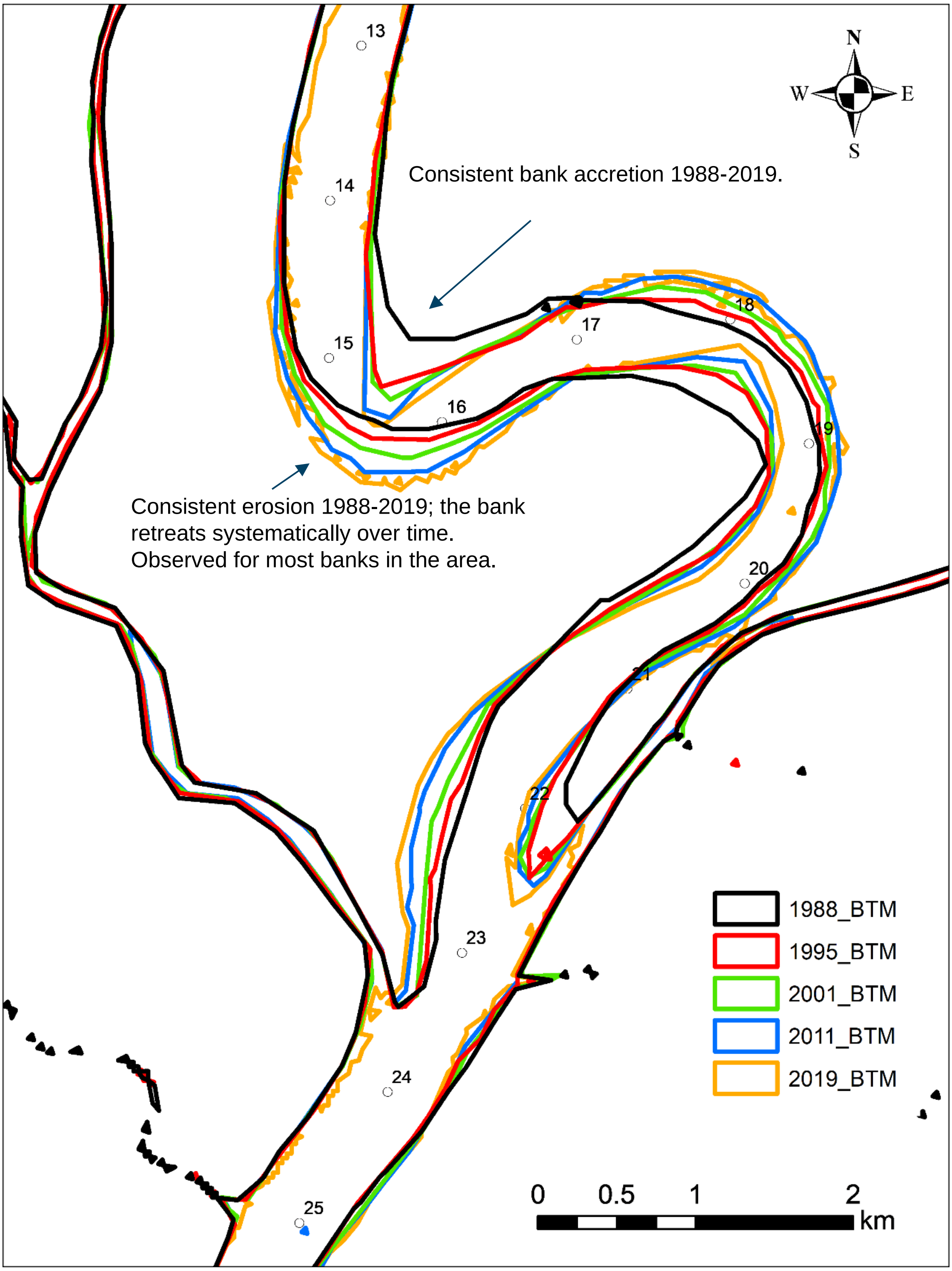

Figure 2-10 Observed bank lines 1988-2019 in the sharp bend upstream.

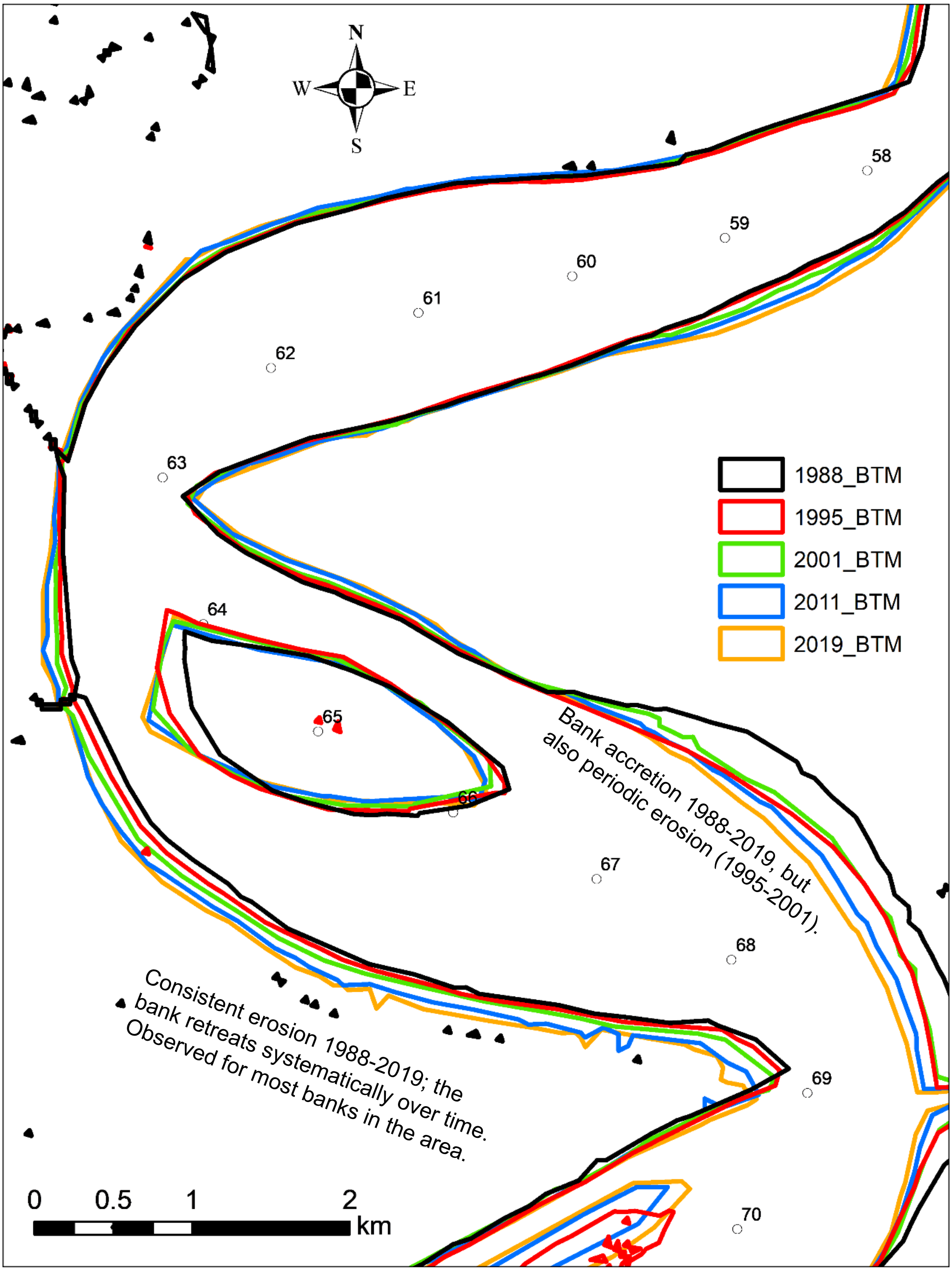

Figure 2-11 Observed bank lines 1988-2019 in the sharp bend downstream.

Detailed bank lines are shown in Figure 2-10 and Figure 2-11 to illustrate that erosion has been systematic since 1988 and that literally all eroding banks are outer bends with large water depths.

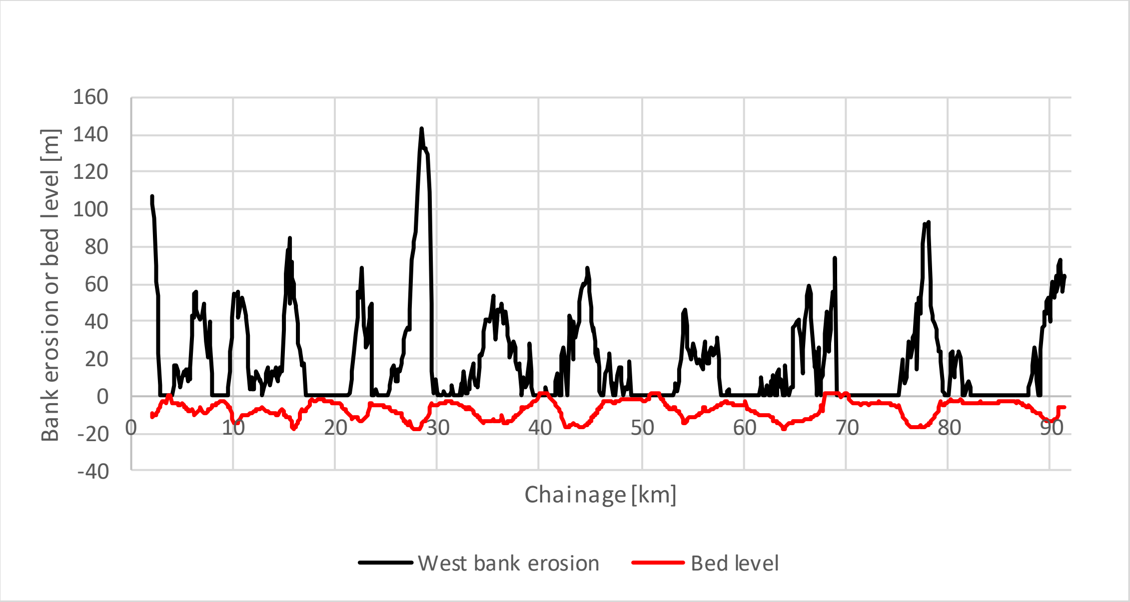

Figure 2-12 Observed west bank erosion 2011-2019 along Bishkhali River as a function of chainage.

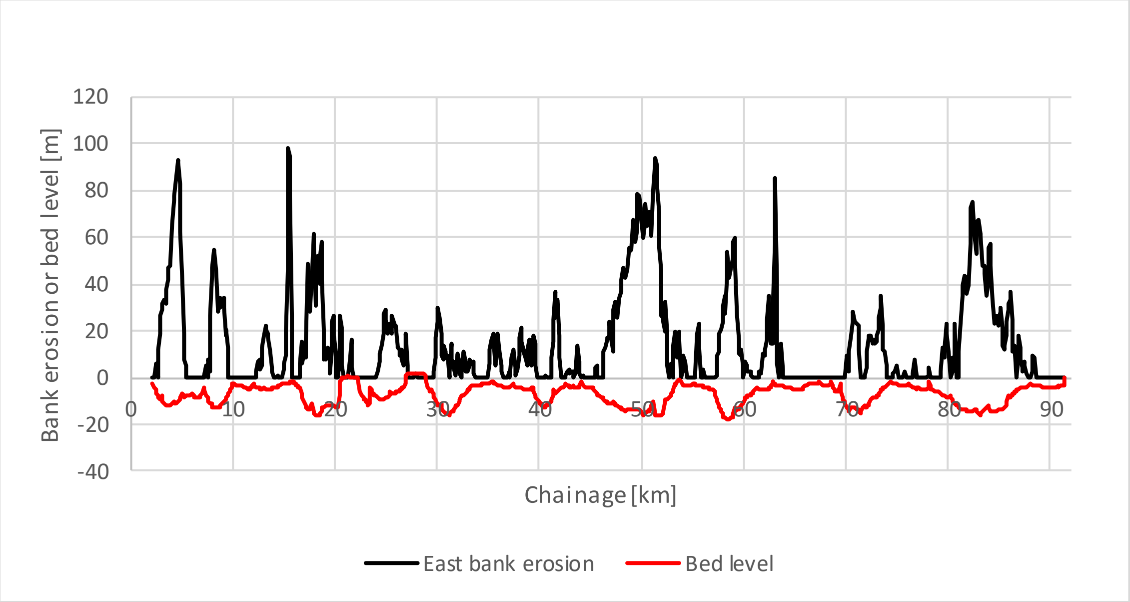

Figure 2-13 Observed east bank erosion 2011-2019 along Bishkhali River as a function of chainage.

The observed bank erosion along both banks as a function of chainages (calculated along the 2019 grid centre line) is shown in Figure 2-12 and Figure 2-13. For illustration of the strong correlation with bed levels, the 2019 bed levels adjacent to the banks were added to the figures.

The surface areas associated with erosion and accretion were integrated from the observations. The resulting accumulated curves are shown in Figure 2-14, which shows that accretion amounts to 54% (same for both banks) of the area associated with erosion. It can also be observed that the two accretion curves have very large local contributions from a few strongly accreting banks, while the eroded area increases more gradually along the river due to more similar contributions.

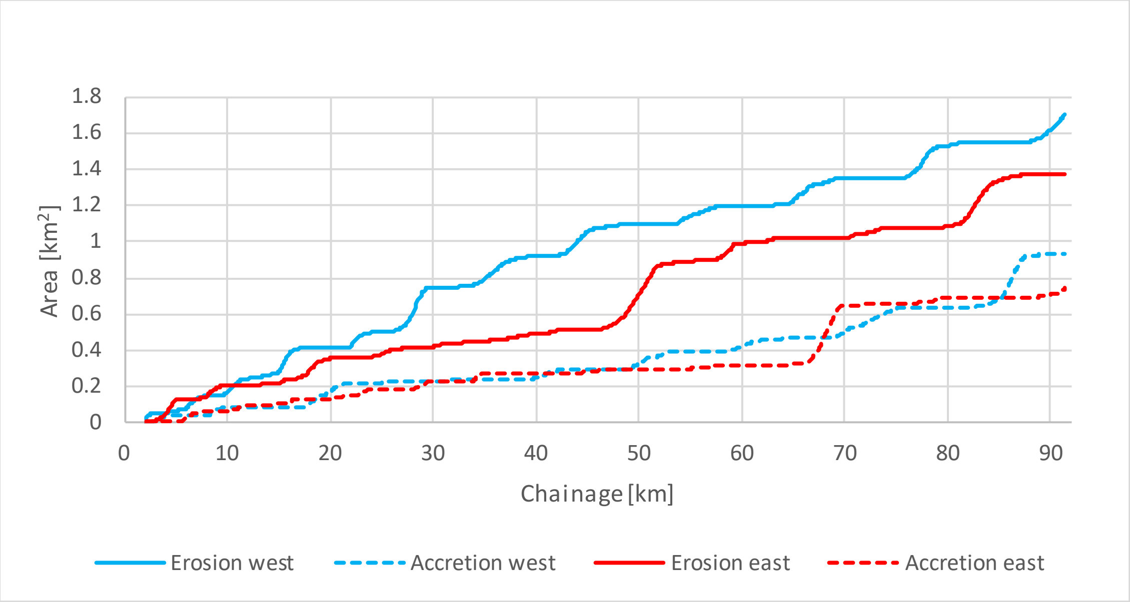

Figure 2-14 Accumulated area curves associated with bank erosion and accretion along each bank and total for the period 2011-2019.

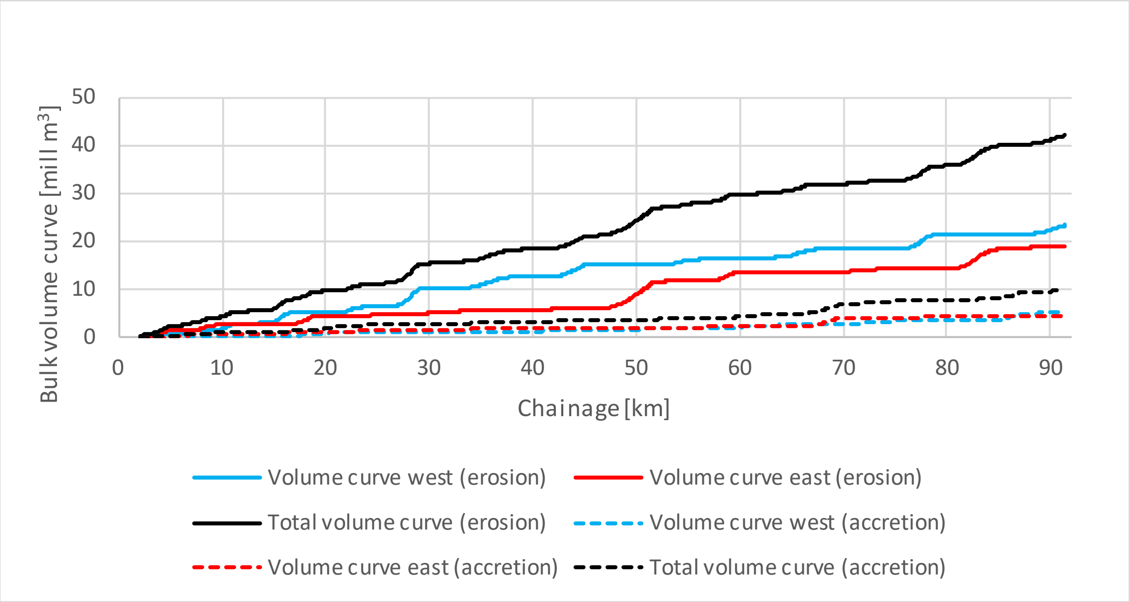

Figure 2-15 Estimated bank erosion accumulated bulk volume curves 2011-2019 for Bishkhali River. For reference accretion volumes were added, which are typically 21-25% of the eroded volumes.

Figure 2-15 shows the bulk volume curves associated with bank erosion, which were locally estimated from:

Volume = $\Delta s * E * (H_b - z)$

Where z was the 2019 bathymetry, bank height H_b=2 mPWD, Δs longitudinal grid spacing, and E observed bank erosion.

The local contributions were integrated to yield the bulk volume curves associated with bank erosion. The bank erosion contribution to the bulk volume is hence around 42 mill m³, which is significant.

Note that bank accretion is not included in the budget. However, although the surface area subjected to bank accretion is 54% of the area subjected to bank erosion, the sediment volumes associated with bank accretion are much smaller due to the very shallow water for accreting banks, while eroding banks have very deep water. The calculated accreted volumes are 21-25% of the eroded volumes. Bank accretion is not directly included in the model but is a passive process in which sedimentation takes place along the accreting bank. The accreting banks are not moved in the model, and therefore not included in the budget.

For the Bishkhali River model it is assumed that the bank porosity is the same for the bank and the riverbed. This is probably not true, as the banks are more compacted. However, there is no data for the particle size distribution in the banks, and it is also possible that the banks contain clay, which will become wash-load when eroded (not morphologically active).

2.6 Subsidence

Subsidence was studied as part of the overall project and processed into a raster.

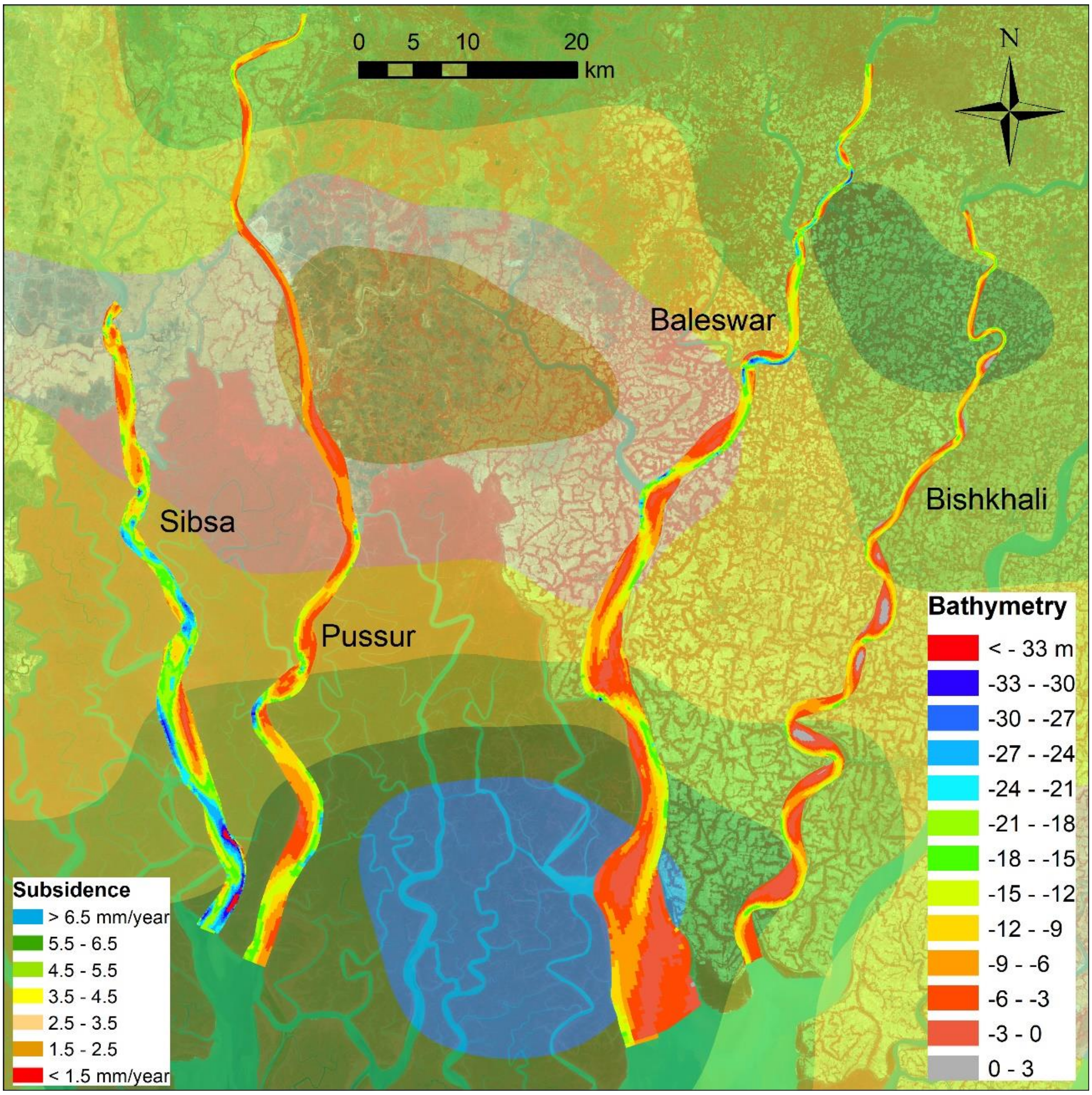

Figure 2-16 Subsidence spatial map in the area where the four models are located.

Figure 2-16 shows the subsidence based on the observations made for the project. The values were contoured to a 100 m raster for use with the MIKE 21C models, and the raster was converted to the individual curvilinear grids.

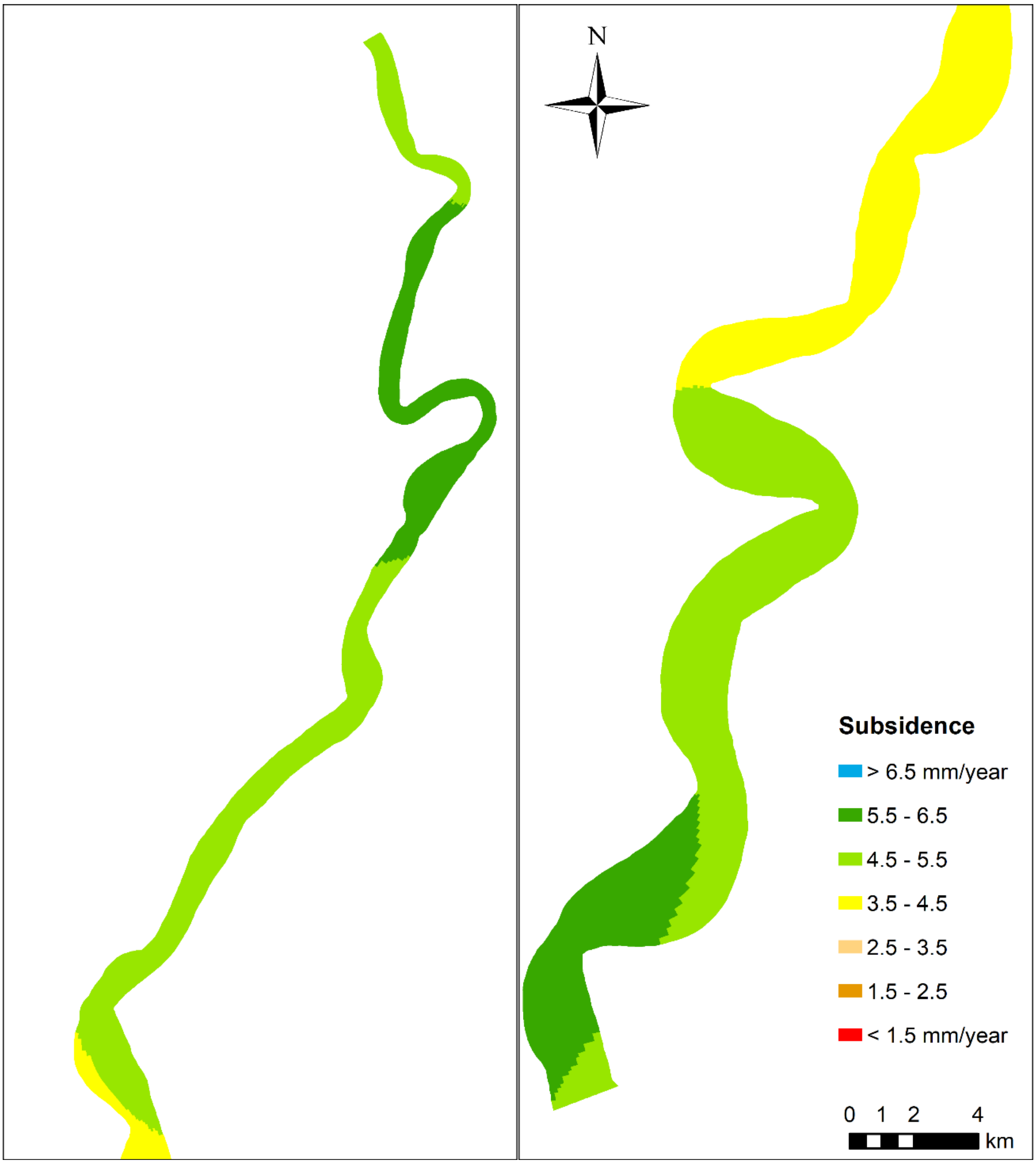

Figure 2-17 Subsidence interpolated to the Bishkhali 2019 model grid.

Subsidence for the Bishkhali is shown in Figure 2-17. The rates are generally around 5 mm/year, which means that over 30 years the riverbed will be lowered by 150 mm. The bed level changes associated with subsidence are hence small compared to morphological changes.

3 Model development

The model development process involves the following components:

- Curvilinear grid conforming to the bank lines
- Bathymetry contoured to the curvilinear grid
- Boundary conditions (upstream, downstream, side channels)
- Hydrodynamic calibration
- Sediment model formulation
- Sediment boundary conditions
- Sediment model calibration
- Bank erosion model calibration

The components are reported in this chapter.

3.1 Grid and bathymetry

Bishkhali River has very limited impact from floodplain due to the polders surrounding the river. Hence, the MIKE 21C model does not have to include a floodplain grid.

Initially, the MIKE 21C model was developed with a high resolution (1199x20). This model was used for initially exploring the hydrodynamics and sediment transport.

Originally, it was not the intention to run models over several years. However, at the time when the Bishkhali River model was developed, the approach had settled on using 2011-2019 hindcasting for model calibration. Although there is only one (2019) bathymetry survey with sufficient resolution for Bishkhali River, it was decided to also use 2011-2019 as calibration period. The reasoning is still the same even though the bed level changes cannot be hindcasted, namely that the planform development also for Bishkhali River is slow and systematic, making 2011-2019 hindcasting ideal for bank erosion calibration (bank erosion being more important than bed level changes).

The grid resolution in the river channel was very high in the initial model. It is important to optimise the grid in the river channel to avoid excessive simulation times for the long-term morphological simulations. The model was subjected to stepwise coarsening until it was deemed that further coarsening would impact the result. In this way the coarsest grid that would ensure a grid-independent result was achieved.

The morphological model runs were conducted on a 799x15 curvilinear grid.

No 2011 model was developed for Bishkali River, although the 2011 bank lines were used for determining bank erosion 2011-2019.

3.1.1 2019 model grid and bathymetry

The 2019 model grid and bathymetry were used for morphological model calibration and validation. Figure 3-1 shows the 799x15 curvilinear grid conforming to the 2019 bank lines, while the 2019 curvilinear bathymetry is shown in Figure 3-2.

The longitudinal cell size (Δs) varied in the range of 32-232 m (average of 113 m), while the transverse cell size (Δn) varied in the range of 17-260 m (average 76 m). For the cell area, the range was 929-53,500 m^2 (average 8,900 m^2).

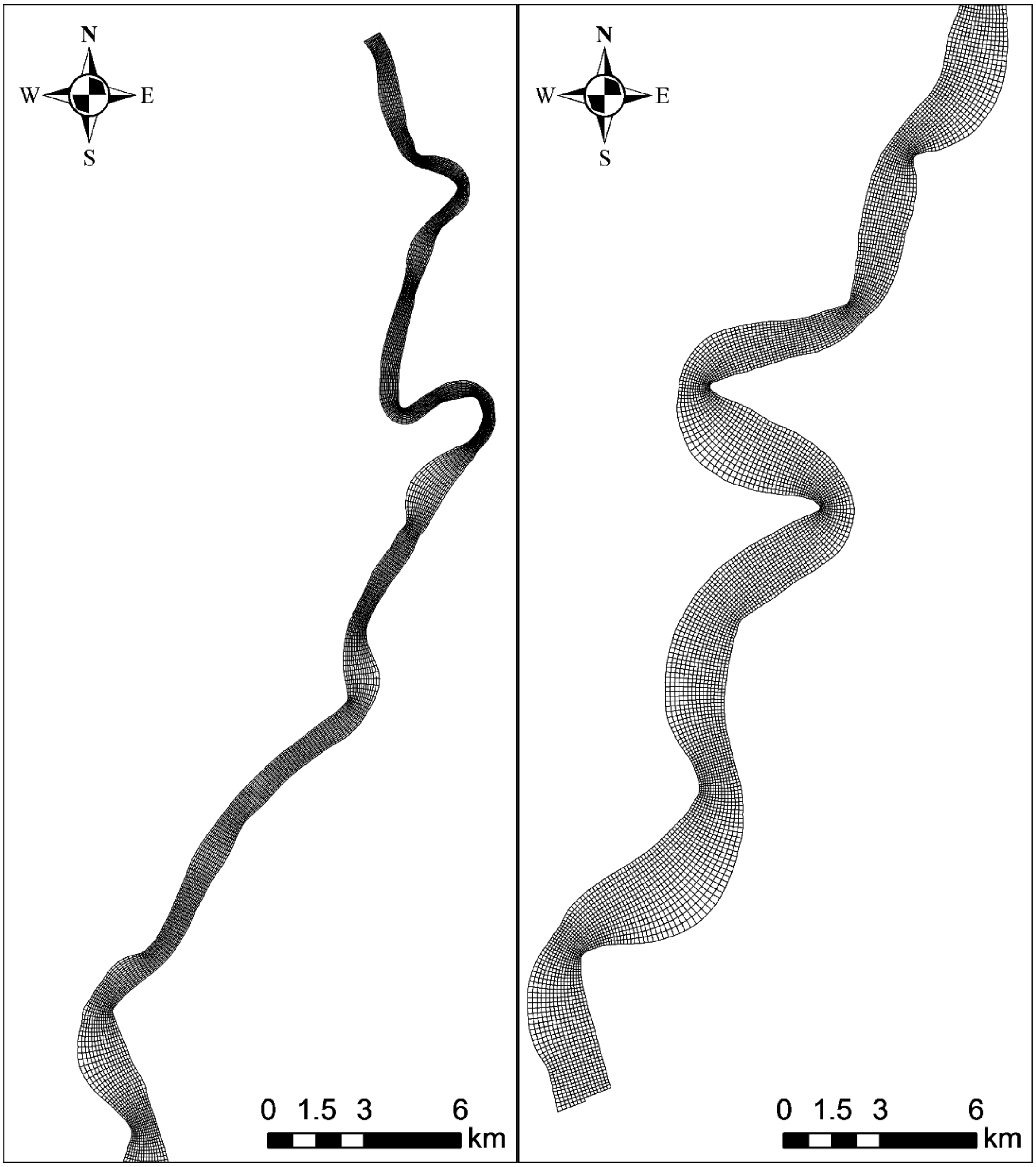

Figure 3-1 Curvilinear grid for the Bishkhali River model based on 2019 bank lines, 799x15 grid cells.

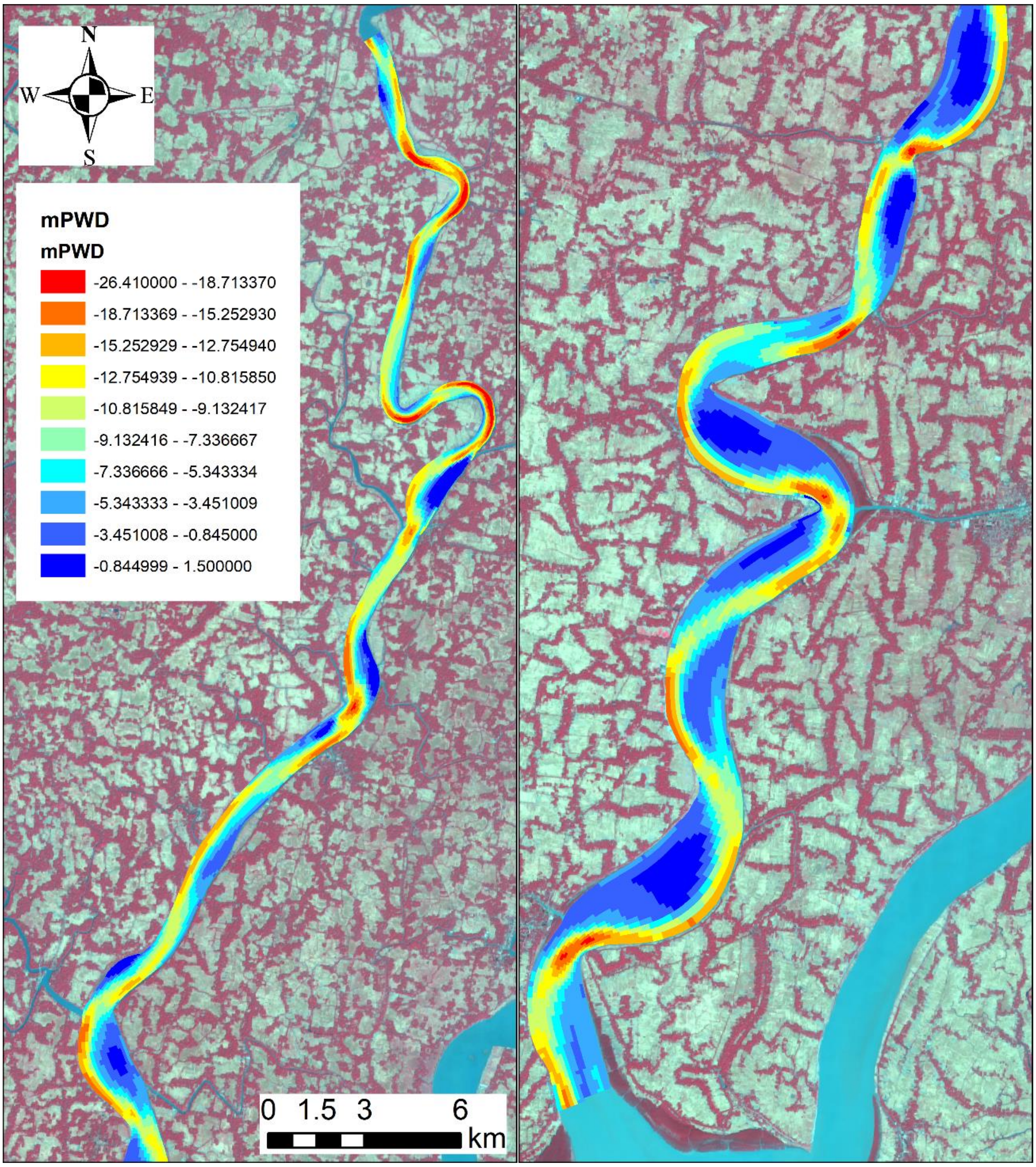

Figure 3-2 Bishkhali River model bathymetry based on the 2019 bathymetry data contoured to the 2019 grid (and 2019 Landsat image).

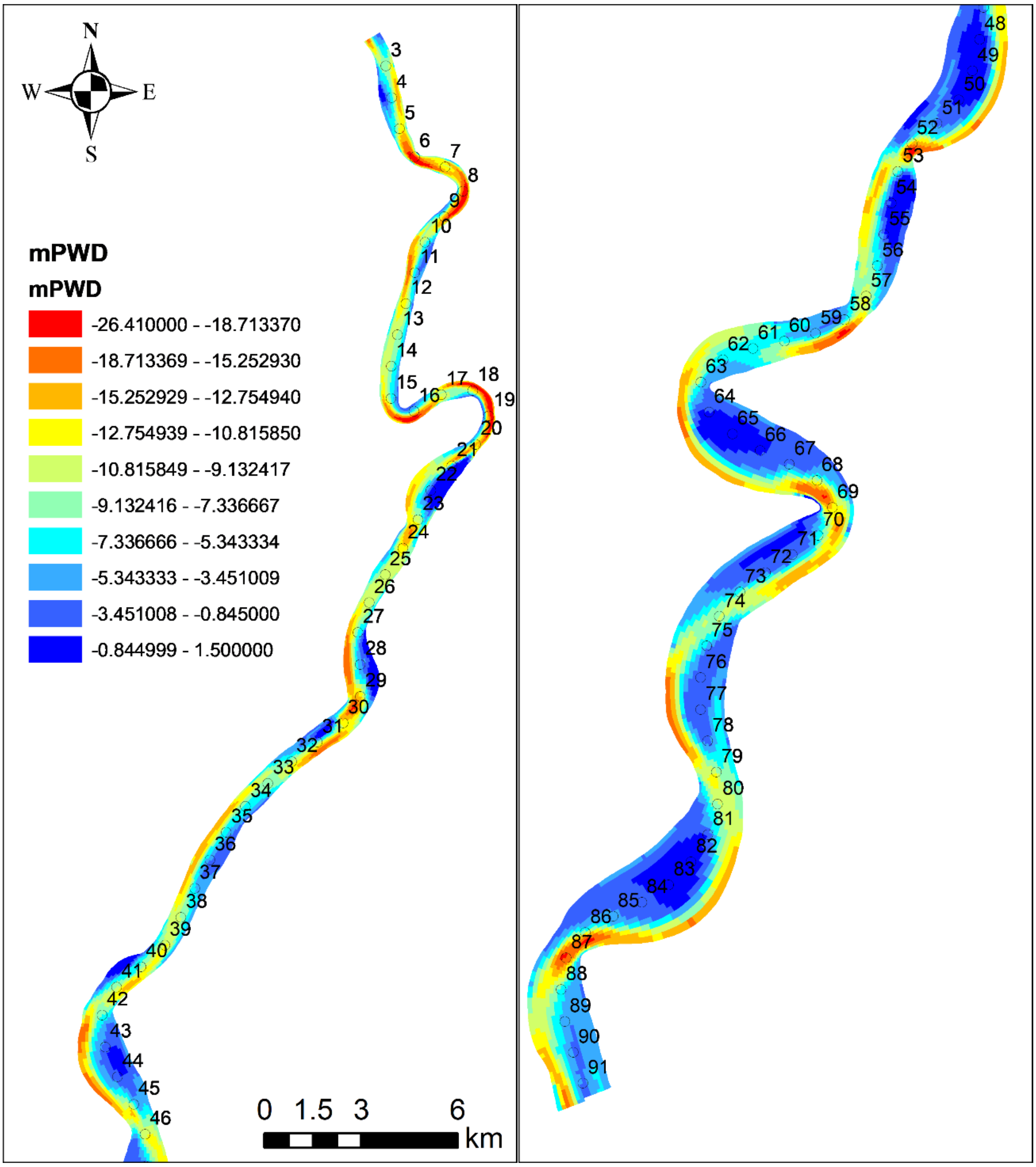

Figure 3-3 Bathymetry with chainages in kilometres along the Bishkhali River.

Figure 3-3 shows the bathymetry with chainages shown for each km along the river axis. The chainages are used as horizontal coordinate for plotting longitudinal profiles along the river, such as volume curves and bank erosion. The chainages align with the MIKE 11 model (SWRM) chainages.

3.2 Hydrodynamic boundary conditions

Inspection of the Bishkhali River Landsat planform showed that the river has only small side channels that feed into the floodplain. There are no significant channels and no channel feeding to other rivers. The small side channels were ignored in the model. Hence, the Bishkhali River model had one upstream boundary and one downstream boundary. As with other models, the upstream boundary is always assigned a discharge, while the downstream boundary is assigned a water level.

Table 3-1 MIKE 21C model boundaries in the Bishkhali River model.

Boundary	SWRM location
Upstream discharge	Bishkhali-560
Downstream water level	Bishkhali-91000

The boundaries of the MIKE 21C model is listed in Table 3-1. For the morphological model runs, IWM provided a continuous time-series for the period 2011-2018 from the SWRM models available for each year. The SWRM is recalibrated each year, hence the time-series for 2011-2019 was merged from 8 individual model runs.

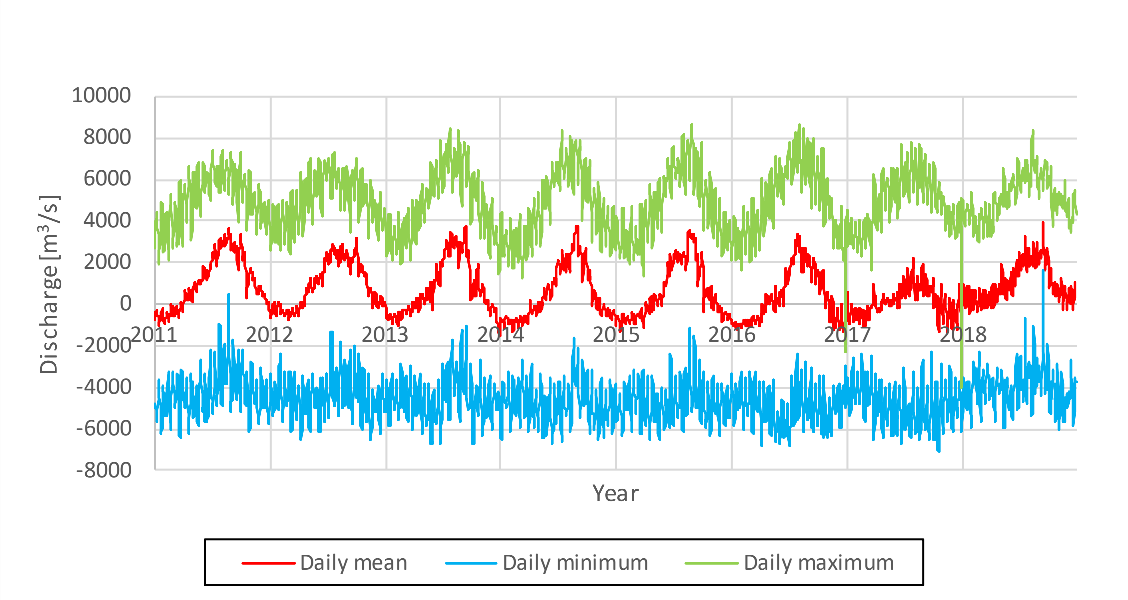

Figure 3-4 Daily minimum, maximum and mean flows 2011-2019 upstream boundary in the Bishkhali River model.

Figure 3-4 shows the daily mean flow (flow averaged over two tidal cycles of 24 hour and 50 minutes) at the upstream boundary along with the corresponding minimum and maximum values.

The figure shows negative daily mean flow at the upstream end of Bishkhali River during the dry season. While there could be flow circulation during the dry season (interaction with other rivers in the area, e.g. Baleswar River), it could also be a shortcoming in the SWRM. No investigation was carried out into why this happens. The results also suggest that the problem was fixed in 2019.

The figure shows that the flow statistics are similar over the years.

The monsoon hydrograph is more pronounced in Bishkhali River compared to the rivers further west, which are more tidal (Sibsa River has almost no net flow during the monsoon). This behavior makes sense, as the Bishkhali River is closer to the Lower Meghna, and it also suggests that the river should be sandier and have higher bank erosion rates than the rivers further west because Bishkhali River has a bigger difference between dry season and monsoon conditions, hence needs to adjust more in the monsoon.

3.3 Hydrodynamic boundary conditions for scenario simulations

The SWRM was used for generating boundary conditions for the MIKE 21C models with the inclusion of subsidence in the SWRM cross-sections and sea level rise in the Bay of Bengal tidal water level conditions, both calculated for the year 2050. A gradual calculation of annual variations from 2019 to 2050 is cumbersome because it would require preparation of new cross-sections every year due to subsidence, so instead only the 2019 and 2050 years were used in the MIKE 21C models. Both years were simulated using the 2019 SWRM without (baseline) and with subsidence and climate change.

IWM ran the SWRM for the period:

- 2 November 2018 00:00
- 29 October 2019 16:30

Results were extracted for the Bishkhali model for the two scenarios:

- Existing conditions (baseline)
- Climate Change and Subsidence (Sub+CC)

Bishkhali has the following open boundaries:

- Upstream discharge
- Downstream water level

There are no side channels in the Bishkhali model.

It is not meaningful to show the full time-series due to the detail. Instead, the tidal time-series were post-processed to show the daily mean, minimum and maximum for the discharges upstream and for the water levels downstream.

Figure 3-5 shows the post-processed daily discharges. The results show that the 2019 SWRM has some dry season net flow, which was not the case with the SWRM model used for the model development. However, the SWRM used for the model development had negative daily mean discharges during the dry season, while the 2019 SWRM has positive net flows. Above all, the post-processed data suggests that the discharges generally increase with subsidence and climate change, which makes sense considering that all tide levels in the Bay of Bengal are increased and the bathymetry is lowered due to subsidence.

The water levels at the downstream boundary daily post-processed values are shown in Figure 3-6. This figure shows the expected rise in the water level due to climate change. The average tidal water level increase at the downstream boundary is 22 cm.

Future sediment concentration boundary conditions were not altered compared to existing concentrations. It should be kept in mind that the model uses sediment concentrations and not sediment fluxes, so while sediment concentrations are considered unchanged in the future, the sediment fluxes can change.

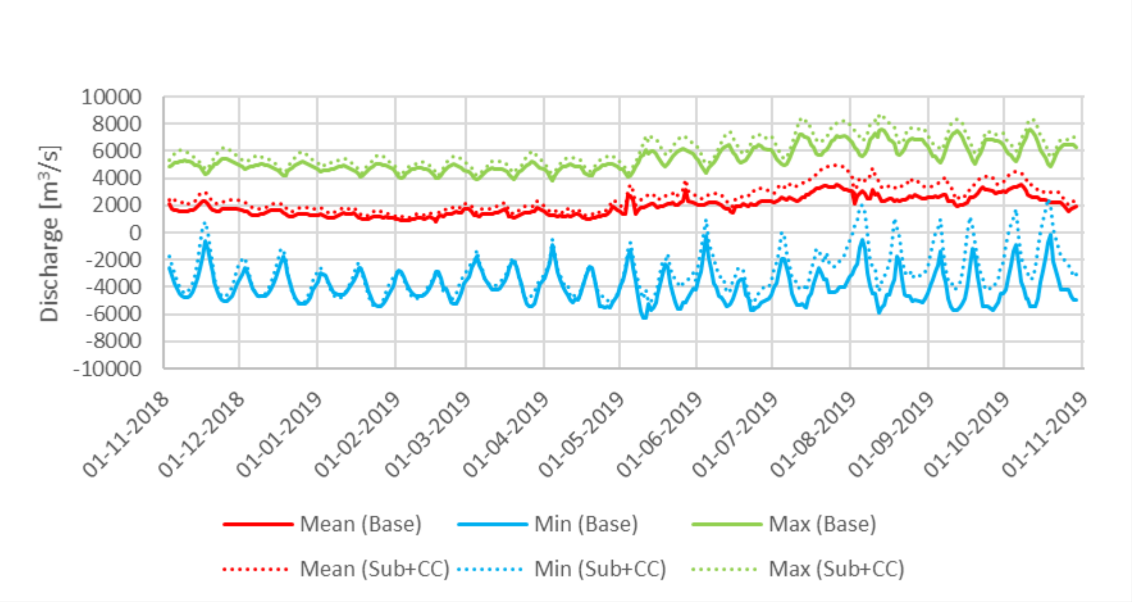

Figure 3-5 Daily minimum, maximum and mean flows 2018-2019 upstream boundary in the Bishkhali River model for the two cases Base and Sub+CC.

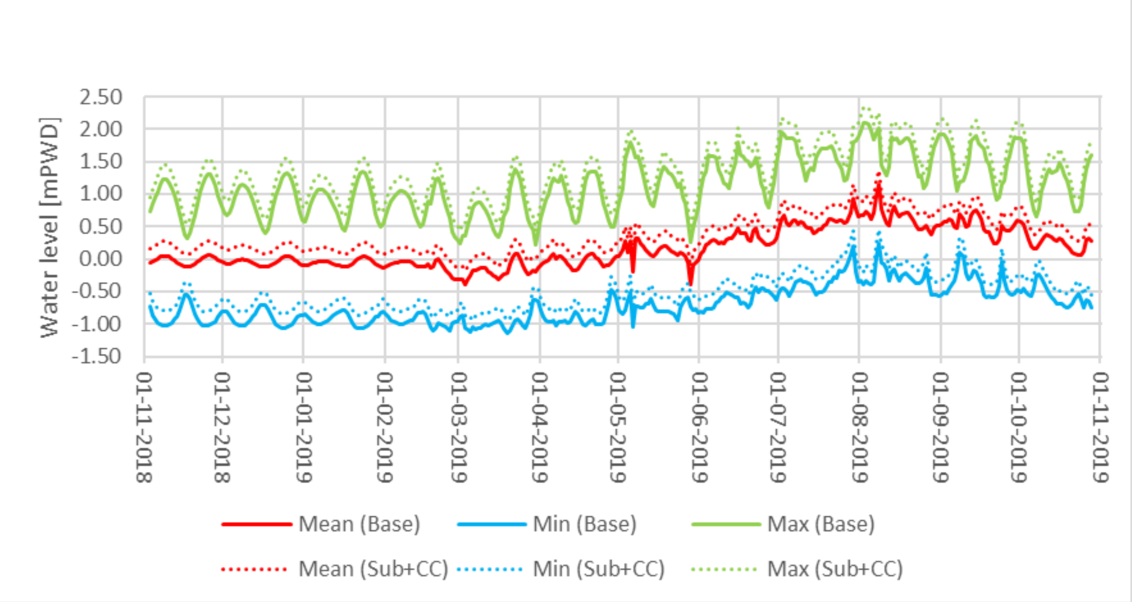

Figure 3-6 Daily minimum, maximum and mean water levels 2018-2019 downstream boundary in the Bishkhali River model for the two cases Base and Sub+CC.

3.4 Hydrodynamic calibration and validation

The calibrated and validated hydrodynamic model is needed to develop a reliable MIKE 21C model capable of predicting sediment transport, bed levels and bank erosion.

The model was calibrated for 2016, while there was not enough data available to validate the calibration parameters. The 2019 grid and bathymetry (being the only available) were used in all calibration simulation. The resistance calibration was partly inherited from the MIKE 11 SWRM. The resistance coefficient used in the hydrodynamic model was Manning M=60 $m^{1/3}/s$.

It is noted that the morphological model was developed with a different resistance formulation, which still yielded good calibration to water levels, but with much higher resistance on bars to deflect the flow. The resistance number in deep channels is most important in the calibration to discharges and water levels, while the shallow water resistance is important morphologically. It is noted that there were no ADCP velocity profiles available for calibration of the spatial flow resistance variation.

The morphological resistance model was revised for the morphological model and not adopted in the hydrodynamic calibration shown here.

3.4.1 Hydrodynamic model calibration 2016

The 2016 hydrodynamic model calibration is presented in this section. Discharge calibrations at Fuljuri are shown in Figure 3-7 and Figure 3-8. The calibration quality is very convincing with both phase and magnitude correctly captured.

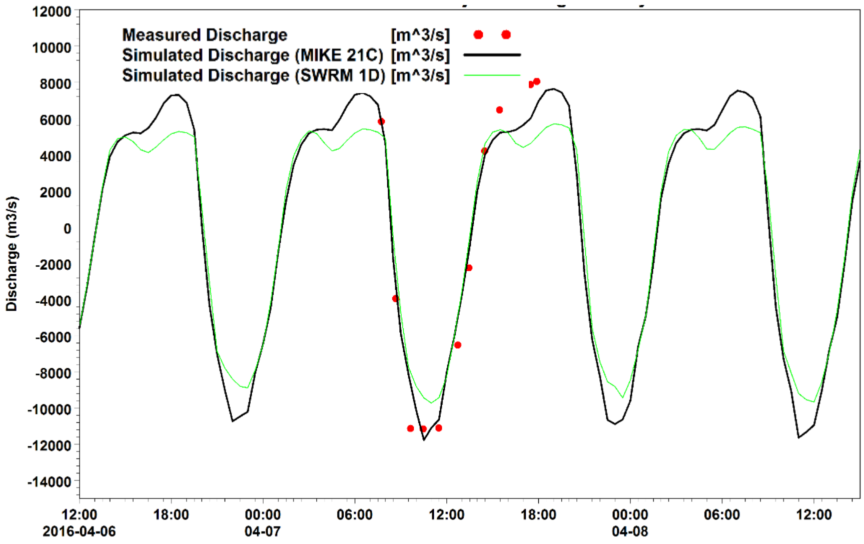

Figure 3-7 Discharge calibration at Fuljuri during dry season (spring) for 2016 (April).

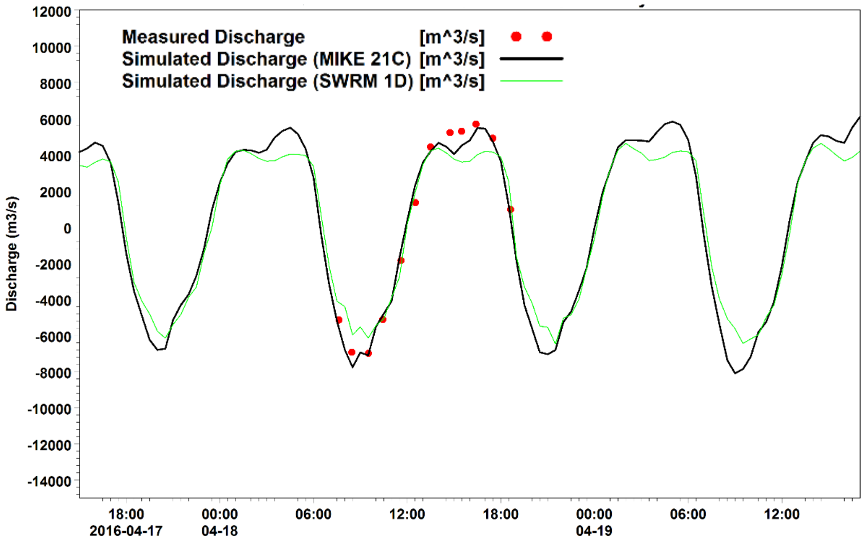

Figure 3-8 Discharge calibration at Fuljuri during dry season (neap) for 2016 (April).

3.4.2 Local hydrodynamic model covering the two sharpest bends

Calibration to observed water levels and discharges can be done using several spatial variations of the flow resistance. In essense there is no unique calibration but a calibration space in which the flow resistance can be made higher on bars and lower in channels to yield the same water levels and discharges, which can be obtained using constant flow resistance numbers. It is difficult to narrow this calibration space without observed velocity profiles in the river bends.

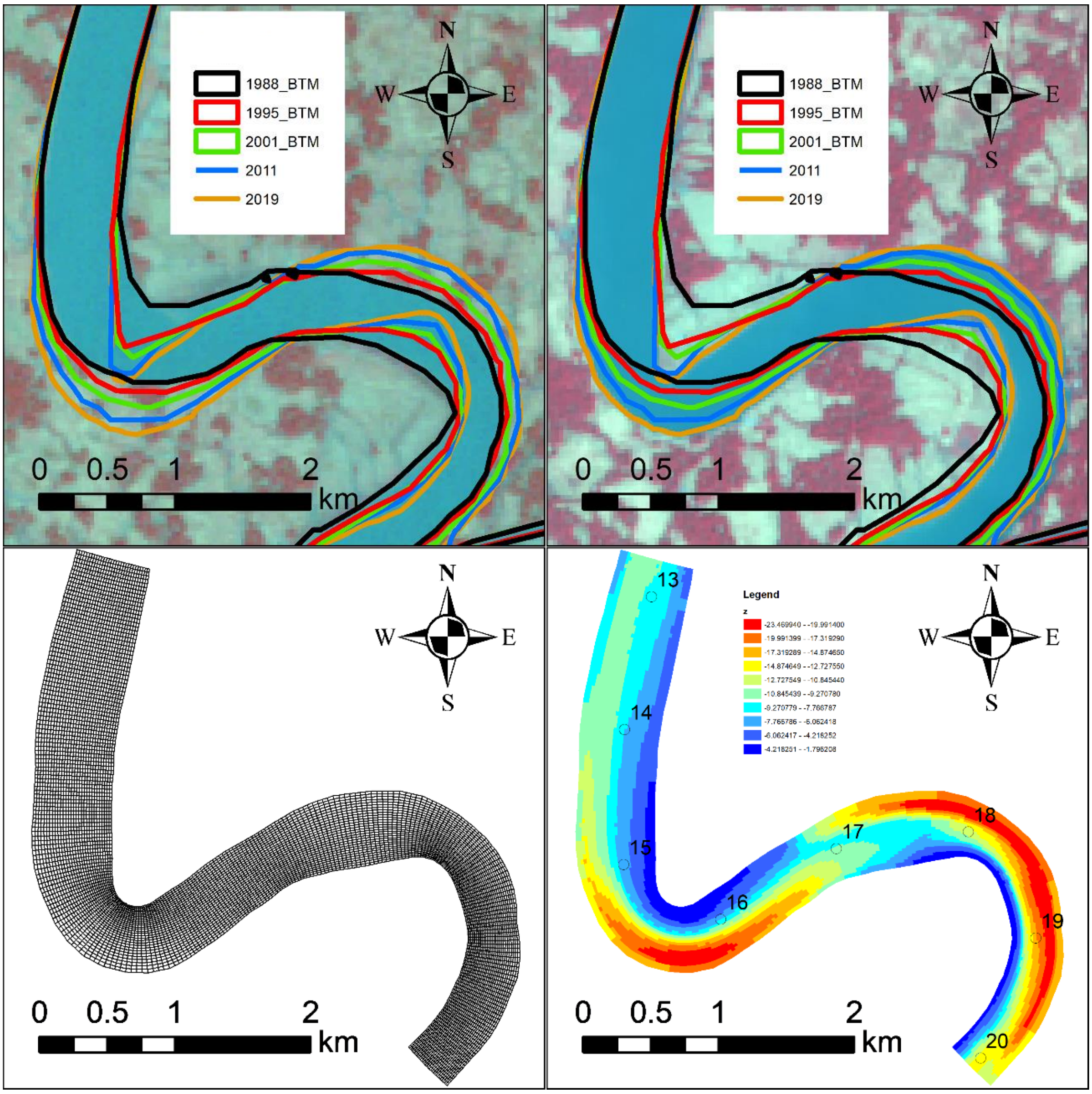

Figure 3-9 Local model covering the sharpest bends (268x30 grid cells). Top left: 1988 Landsat with bank lines 1988-2019, top right: 2019 Landsat with 1988-2019 bank lines, bottom left: 2019 curvilinear grid, bottom right: 2019 bathymetry.

No ADCP velocity profiles are available for calibration of the spatial resistance distribution. Although ADCP data has been collected in the rivers, IWM – for good reasons – always collects the ADCP profiles in straight reaches, while bends are far more important to understand for the morphology. In particular, the deflection of flow from bars into deep water is critically important in shaping the bed morphology and hence bank erosion.

To invesigate the flow distributions in the sharp bends, a local model was developed for the sharpest bend located upstream in Bishkhali River.

The local model has a higher resolution compared to the overall model. Figure 3-9 shows the 1988-2019 bank lines as well as the local grid and bathymetry.

Constant boundary conditions were applied to simplify the problem and avoid too long runtime when using MIKE FM 3D. The upstream discharge was set to 8000 m^3/s, while the downstream water level was set to 2 m (estimated from model runs).

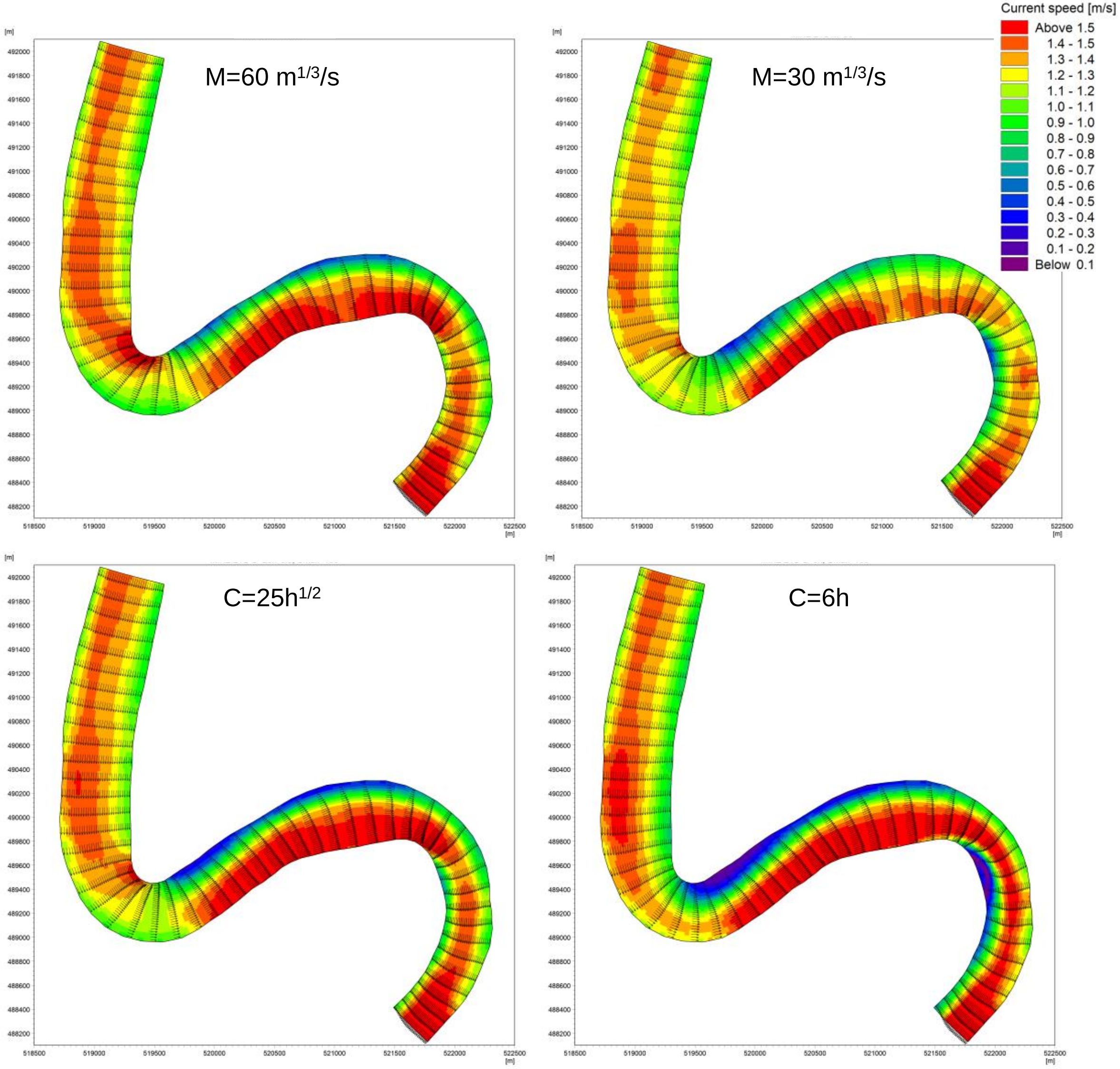

Figure 3-10 MIKE 21C results for 1) Manning M=60 $m^{1/3}$/s, 2) Manning M=30 $m^{1/3}$/s, 3) alluvial resistance model C=25$h^{1/2}$, 4) extreme alluvial resistance model C=6h.

MIKE 21C results for varying resistance models are shown in Figure 3-10:

- M=60 $m^{1/3}$/s
- M=30 $m^{1/3}$/s
- C=25$h^{1/2}$
- C=6h

The results for M=60 $m^{1/3}$/s correspond to the calibrated hydrodynamic model, and it can be seen from the figure that M=60 $m^{1/3}$/s gives very weak topographical steering, which causes quite strong shortcutting flows over the bars. The results for M=30 $m^{1/3}$/s are very different with the bars deflecting the flow much more strongly. It is noted that M=60 $m^{1/3}$/s is calibrated in the sense that it gives correct discharges, but M=60 $m^{1/3}/s$ is not realistic for sand. On the other hand, M=30 $m^{1/3}/s$ is too low for a mud bed, while it is suitable for a sandy bed. Obviously M=30 $m^{1/3}/s$ would not calibrate to water levels or the discharges shown under the calibration section, while M=60 $m^{1/3}/s$ gives too weak topographical steering.

MIKE 21C has an alluvial resistance model which can be made to react more to the flow depth compared to the Manning model. In the alluvial resistance model the Chezy number (C) is calculated from:

$$C = ah^b$$

Where a and b are coefficients and h the water depth. The Manning resistance model already follows this form due to:

$$C = Mh^{1/6}$$

The idea of the alluvial resistance model is that the high resistance on bars associated with dunes and ripples or simply a sandy bed versus the muddy bed in the flow channels can be replaced by a correlation of the resistance to the water depth because the bars are shallow, while the deeper channels are mud-covered and hence have lower resistance. This does not necessarily work in general and may cause unwanted consequences when applied in a model, such as triggering unrealistic bar formation due to too enhanced flow deflection.

The water depths on the bars are typically 5 m, and dunes can cause the total resistance to be 4 times higher than skin friction (i.e. 75% form friction), so having C=6h means that the Chezy number is C=30 $m^{1/2}/s$ on the bars, which is necessary to significantly deflect the flow, while C=25$h^{1/2}$ means much higher Chezy numbers around 50 $m^{1/2}/s$ on the bars. Both models yield significantly higher Chezy numbers in the deep outer bend, so they will both calibrate well to observed water levels (the deep water resistance is most important for tidal propagation), while they still give very different velocity profiles, as seen in Figure 3-10.

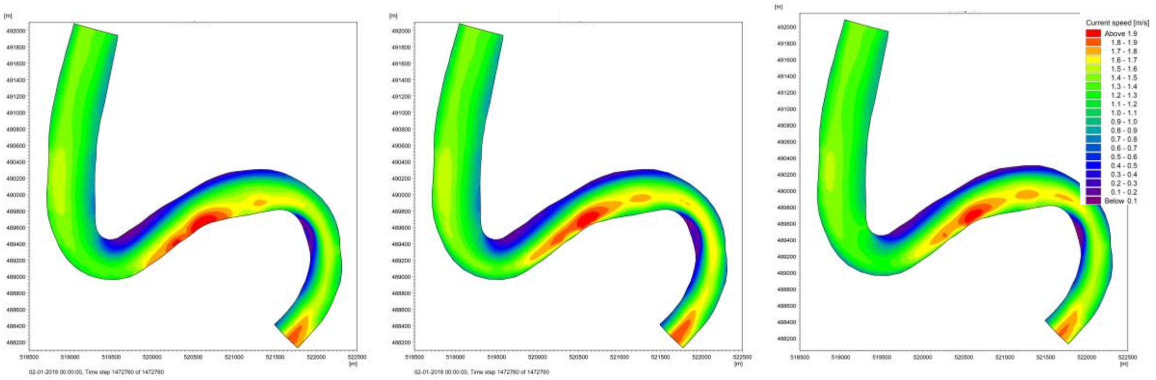

Figure 3-11 Model results for extreme alluvial resistance model C=6h. From left: 1) MIKE 21C, 2) MIKE FM 2D, 3) MIKE FM 3D. MIKE FM includes sidewall friction.

Figure 3-11 shows a comparison between MIKE 21C and MIKE FM. This comparison is done to verify that the two models give similar results, allowing for comparison also with MIKE FM results using its 3D solver. The comparison is made for the extreme alluvial resistance model C=6h. The MIKE FM results were calculated for 2D and 3D to investigate the impact of 3D. The results are very similar suggesting that 3D effects (e.g. secondary flow convection) are of less importance. The comparison of the results from MIKE 21C and MIKE FM shows that 3D has a very small impact on the velocity distribution.

It can be concluded that the calibrated Manning M=60 m$^{1/3}$/s produces very weak topographical steering, which causes high flow velocities along the inner bends. This Manning M corresponds to mud. The lower Manning M=30 m$^{1/3}$/s produces more topographical steering, which seems more realistic, and this lower Manning M is reasonable for sand. The alluvial resistance model designed to mix these two resistance magnitudes with low resistance in channels and high resistance on bars can be tuned to yield the same water levels as the low resistance, but with significantly different velocity profiles in the bends due to flow deflection. It was also shown that 3D effects are unimportant, which should also be expected due to the large width to depth ratios of the Bishkhali River, even though the curvature is very high in the considered bends.

It is clear from the results that the flow resistance model is important for the morphology. The very weak topographical steering for a constant Manning M=60 m$^{1/3}$/s gives rise to concerns due to the obvious difficulties that must be expected from this Manning M when trying to correctly reproduce sand bars.

3.5 Sediment model

A 2-fraction sediment model was adopted with:

- Silt 0.05 mm (cohesive)
- Sand 0.125 mm (non-cohesive)

The cohesive sediment was modelled using the traditional cohesive sediment erosion (E) and deposition (D) functions, see Mehta et al. (1989).

The erosion rate [g/m^2/s] was calculated from:

$$E = F_i E_0 \left(\frac{\tau'}{\tau_{ce}} - 1 \right)^n, \tau' > \tau_{ce}$$

The deposition rate [g/m^2/s] was calculated from:

$$D = w_s \, \gamma_0 \, C \left(1 - \frac{\tau'}{\tau_{cd}} \right), \qquad \tau' < \tau_{cd}$$

Where:

F_i	Relative mass of the fraction (i) in the bed surface
E	Erosion rate [g/m^2/s]
D	Deposition rate [g/m^2/s]
E_0	Erosion coefficient [g/m^2/s]
τ'	Skin friction shear stress
τ_{ce}	Erosion shear stress threshold [N/m^2]
τ_{cd}	Deposition shear stress threshold [N/m^2]
C	Simulated concentration [g/m^3]
w_s	Fall velocity [m/s]
n	Exponent (non-linearity)
γ_0	Ratio between near-bed and depth-integrated concentration (optional)

The calibrated parameters were:

τ_{ce} = 0.2 N/m^2

τ_{cd} = 0.1 N/m^2

E_0 = 0.02 g/m^2/s

w_s = 1 mm/s

n=1

γ_0 = 1

Porosity 0.6

The sand was modelled with fall velocity calculated from Rubey (1933), using a water temperature of 28 degrees centigrade, and suspended load calculated from Garcia & Parker (1991). The sand porosity was set to 0.35.

The initial bed composition was estimated by using the elevation as a proxy for bars and assigning sandy values to bars and silty values to channels. There were only three bed samples in the whole river, so the bed composition map was very uncertain.

A simple alluvial resistance model was used for deflecting flow away from bars in which the local Chezy number was calculated from the water depth:

$C = 25h^{1/2}$

The alluvial resistance model was adjusted to yield resistance numbers comparable to the hydrodynamic model-calibrated Manning M=60 m$^{1/3}$/s to simulate comparable water levels. To obtain comparable water levels, the resistance numbers should be comparable in the main flow channel, while higher resistance on the bars will deflect the flow away from bars without compromising the hydrodynamic calibration. The lack of data (especially bed surface sand content and velocity profiles) makes it difficult to apply a more advanced description, i.e. using a regime predictor to determine dune cover.

3.6 Sediment transport boundary conditions

There were two boundary conditions in the Bishkhali River model:

- Upstream concentration C(Q)
- Bay of Bengal concentration (constant)

Due to the nature of the advection-dispersion equation for the suspended sediment concentration, the boundary conditions only applied for inflow to the model area. Hence, there was only a need for the upstream sediment concentration for ebb flow and downstream sediment concentration for flood flow.

A curve fit was developed for the total sediment concentration as a function of the discharge (see also Figure 2-8) for ebb flow. The curve was based on the Fuljuri data for which the correlation with discharge is better than for Kakchira:

$$C(Q) = C_0\left(\frac{Q}{Q_0}\right)^2$$

With C_0=800 g/m^3 and Q_0=10,000 m^3/s.

It was assumed that clay contributed by 80% of the total concentration, and 80% of the non-clay portion was assumed to be silt, i.e. 80% clay, 16% silt and 4% sand in the total concentration. There was no data available to support these choices.

Considering that the downstream concentration has very little influence on the results, constant values were assigned. The silt fraction was set to 80 g/m^3, while the sand fraction was set to 20 g/m^3. The values have very little influence on the model behaviour.

3.7 Calibration against observed bed level changes 2011-2019

The best way to calibrate a morphological model is always to hindcast the observed morphological development. For Bishkhali River, the 2019 bathymetry survey collected for the study is the first (known to the project) bathymetry survey of the river with sufficient detail for 2D contouring, and hence there is no basis for calibrating against observed bed level changes.

The 2009 bathymetry data with insufficient resolution for 2D contouring was used for comparing to observed changes in the longitudinal sediment volume distribution. Although not ideal, it offered the best basis for determining whether the sediment transport in the Bishkhali River was modelled reasonably.

The initial and simulated bathymetry after the hindcast are shown in Figure 3-12.

The initial bathymetry was 2019 along with the 2019 planform. Hence the simulation does not represent a real hindcast. The ideal is obviously to conduct the 2011-2019 hindcast, but it cannot be done.

It is observed that sand deposits on the side slopes of the bars, but some of the bars are not realistically simulated. It is known from other models studied in the project, especially Pussur River, that the bar formation is sensitive to the flow resistance and sediment composition of the bars. For Bishkhali River there is very little data available for the sediment composition and no measured velocity profiles in the river bends.

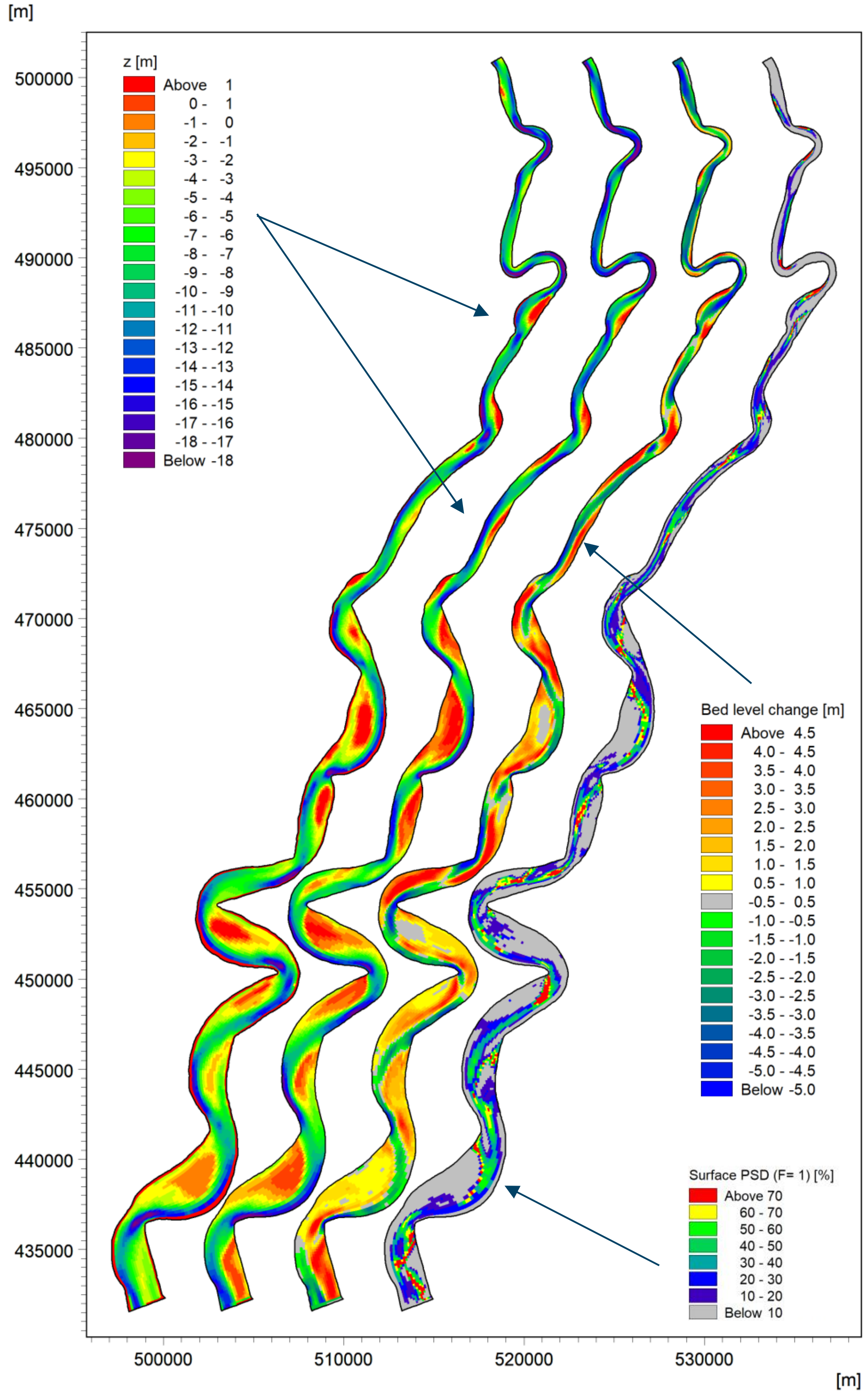

Figure 3-12 Morphological hindcast results 2011-2019 (note the different colour scales). From left: 1) initial bathymetry (2019), 2) simulated bathymetry after 8 years (would then be 2027), 3) simulated bed level changes after 8 years, 4) simulated bed surface sand content.

3.8 Longitudinal validations

The model was validated to the extent possible against the observed integrated bulk volume curve 2009-2019, which is for a different period than the hindcast (2011-2019). The purpose of the comparison is to use the 2009 bathymetry data, which is the only available bathymetry data.

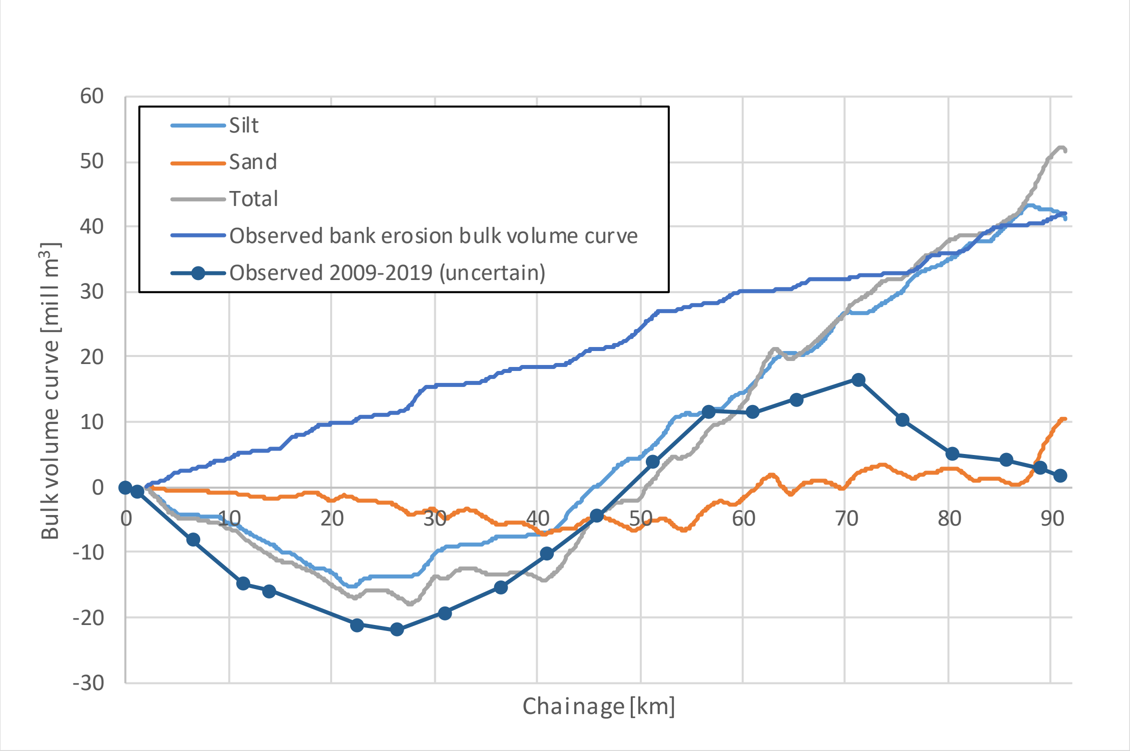

Figure 3-13 Comparison of observed (uncertain) 2009-2019 and simulated 2011-2019 integrated bulk volume curves. The simulated results were divided into silt and sand, which obviously cannot be done for the observations.

The integrated bulk volume curves are compared in Figure 3-13. It should be kept in mind that the “observed” bulk volume curve is uncertain and not for the same period (boundary conditions were provided by IWM for 2011-2019 on request from the project).

It should also be kept in mind that the initial bathymetry in the “hindcast” was 2019, i.e. it is not actually a hindcast.

Having made the shortcomings clear, there are some interesting things to say about the bulk volume curves:

- The bank erosion bulk volume curve is higher than the simulated
- The sand bulk volume curve exhibits an apparent peculiar wavy behaviour
- The silt dominates
- The simulated bulk volume in the downstream end is likely to be sensitive to the downstream boundary condition used in the model
- The simulated bulk volume corresponds remarkably well to the (rather uncertain) observed values, except downstream

These are discussed in the following.

Bank erosion has clearly a large impact on the sediment budget in the Bishkhali River. The integrated bulk volume curves show that the river was fed a lot of sediment from bank erosion, in fact more than what was deposited, so the remaining bank erosion products were transported out. Here it should be kept in mind that it is the observed bank erosion bulk volume curve, which must be considered reasonably accurate.

The wavy pattern of the sand curve is due to sand bar changes. There is surely some readjustment of the initial sand deposits in the river and some deposition of bank material eroded along outer bends and deposited on downstream sand bars.

The silt clearly dominates, which is imposed by the upstream boundary and bank material contributions, which are mainly silt. It is not known whether this is correct due to the lack of particle size distribution data for the banks.

In the downstream end it is known that the upstream penetration of the downstream boundary condition is around 20 km over the considered hindcast period, which is a length scale also seen in the other models developed during the project. It is possible that the downstream silt concentration is set too high, but this is not important. The observed bulk volume suggests that overall the Bishkhali River was neutral in its sediment budget for 2009-2019, which could surely also be obtained in the model simulation 2011-2019.

The simulated shape of the bulk volume curve aligns well with the (uncertain) observations. The results suggest that the upstream end of Biskkhali River was erosional and the downstream end depositional, which aligns with the observations. It should also be kept in mind that the initial bathymetry for the “hindcast” was the 2019 bathymetry, so redistribution of sediment from upstream to downstream is to some extent already included in the 2019 bathymetry, and one would expect the same redistribution to be weaker in a model.

The main purpose of this comparison was to demonstrate that the Bishkhali River model has a reasonable handle on the sediment transport in the river. The comparison to the integrated bulk volume curve 2009-2019 shows that the sediment transport is reasonably simulated in the model.

3.9 Bank erosion model

Several bank erosion formulas were tested during the developments of the models. A formula based on Hasegawa (1989) was selected as the most optimal formula:

$$E = E_h\,|V|\left(1-\left(\frac{h_c}{h}\right)^{2/3}\right)$$

Where E is the erosion rate [m/s], E_h a non-dimensional calibration parameter, V is the near-bank flow velocity [m/s], h the near-bank water depth [m], and h_c the critical water depth [m] below which no erosion takes place. Calibration simulations resulted in the following parameters in the derived Hasegawa (1989) bank erosion formula:

$E_h = 1.5 \times 10^{-6}$

$h_c = 10$ m

The calibration result is presented and discussed in the following.

The value of E_h in the other three models (Sibsa, Pussur, Baleswar) was $E_h=10^{-6}$, so the Bishkhali River calibrated erosion coefficient was 50% higher. This aligns with the observation from processing the bank lines, namely that the bank erosion rates in Bishkhali River are distinctly higher.

Physical justification can be found for increasing the erosion in the Bishkhali River model compared to the other models, namely that the Bishkhali River is not located in the Sundarbans (less vegetation), and it is also possible that the river is sandier than the rivers further west. Less vegetation and less cohesion in the banks will cause higher bank erosion rates. The higher bank erosion is fully expected from Hasegawa (1989) in which the equivalent to E_h is derived from hydraulics and sediment properties.

The calibration result is presented and discussed in the following.

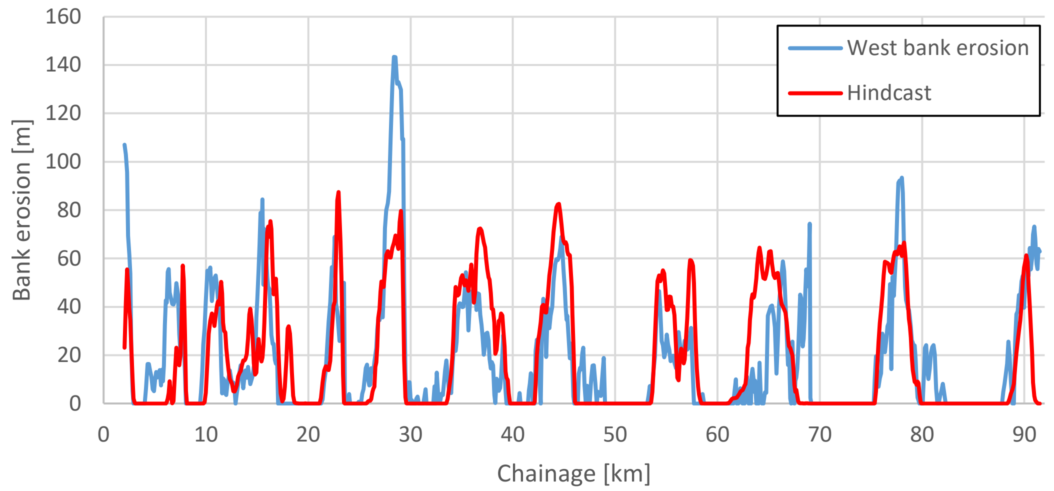

Figure 3-14 Observed and simulated west bank erosion for the Bishlhali River model 2011-2019.

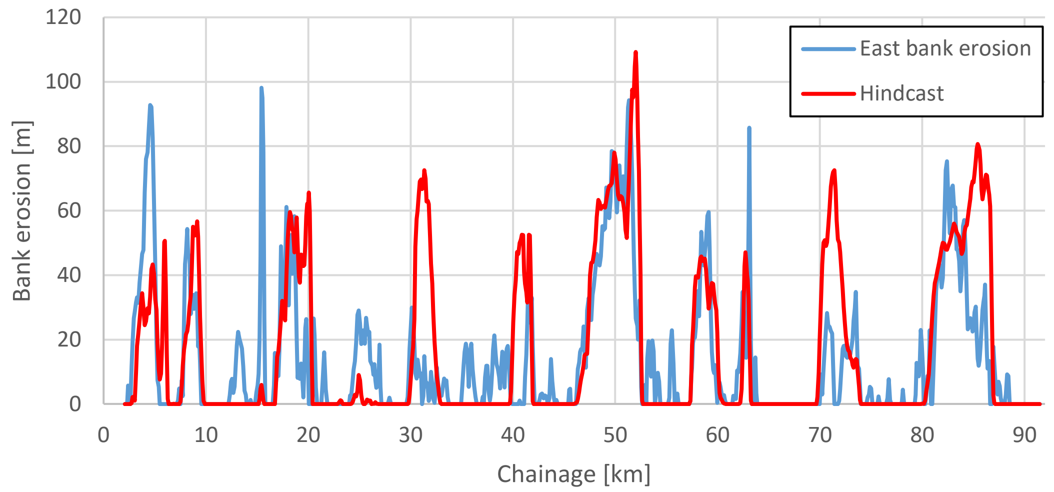

Figure 3-15 Observed and simulated east bank erosion for the Bishlhali River model 2011-2019.

The observed and simulated bank erosions along the river are compared in Figure 3-14 and Figure 3-15. It should be kept in mind that the initial bank line was from 2019 along with a 2019 bathymetry, i.e. it is not a true hindcast. The figures show very good agreement between the observed and simulated bank erosion.

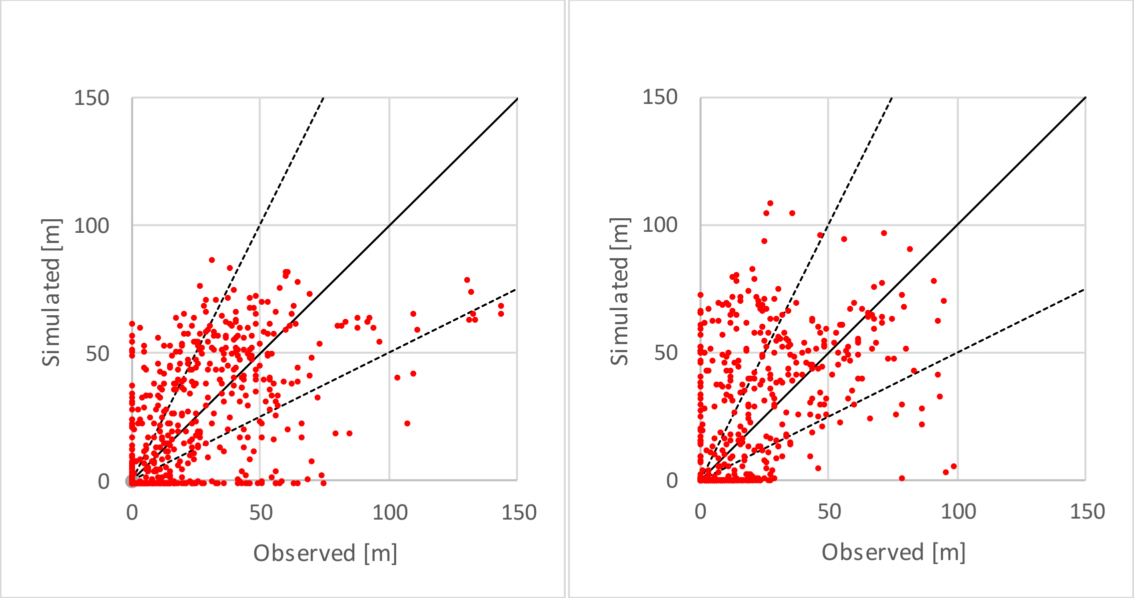

Figure 3-16 Comparison of observed and simulated bank erosion. The solid line is perfect agreement, while the dashed lines are +/- 50%. One dot is shown per grid point along each bank line.

Going into the quantities, it can be seen from Figure 3-16 that especially the high bank erosion rates along the western bank are underpredicted. The average bank erosion rates match well, so it is difficult to argue for changes of the E_h. Ultimately the shortcomings are probably not related to the bank erosion formula, but to what is fed into it. Due to the existence of only one detailed bathymetry survey (2019), it is not known whether the bed levels are correctly predicted in the Bishkhali River model, but it is known that bend scour levels are sensitive to the sediment model parameters. The bed scour levels have a lot of impact on bank erosion.

3.10 Simulated bank line movement with dynamic grid updating

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 grid, leading to many complications when post-processing the results. 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 2011-2019. However, for longer model runs, the feedback between planform and bathymetry must be accounted for. Considering that the application model should run much longer timescales compared to 2011-2019, the application model was prepared for using dynamic grid updating.

For Bishkhali River, comparison could not be carried out to observed bank lines in 2019, as it was done for the other three models. The reason is that there was no 2011 bathymetry for Bishkhali River, and therfore the 2011-2019 “hindcast” was performed using the 2019 bathymetry and 2019 bank lines.

However, initial (2019) and simulated (after 8 years) bank lines can still be compared to illustrate that the bank erosion is working properly. Essentially the results show what can be interpreted as 2027 bank lines, if the 2011-2019 hydrograph repeats again in 2019-2027. One of the main conclusions from the overall study is that the bank erosion prediction is not very sensitive to the hydrograph, which also shows a very consistent annual variation when it comes to the monsoon net flows, while the tidal flows are very similar each year.

Figure 3-17 shows the overall initial (2019) and “hindcasted” (2027) bank lines. At this detail level, the bank line movement cannot be clearly identified, so detailed zooms were extracted in the two local areas shown in the rectangles.

Figure 3-18 shows the detail in the upstream sharp bend, and it can be observed that the bank line movement is like the observations 2011-2019 (Figure 2-10). Figure 3-19 shows the downstream sharp bend for which similar observations can be made regarding comparison to 2011-2019.

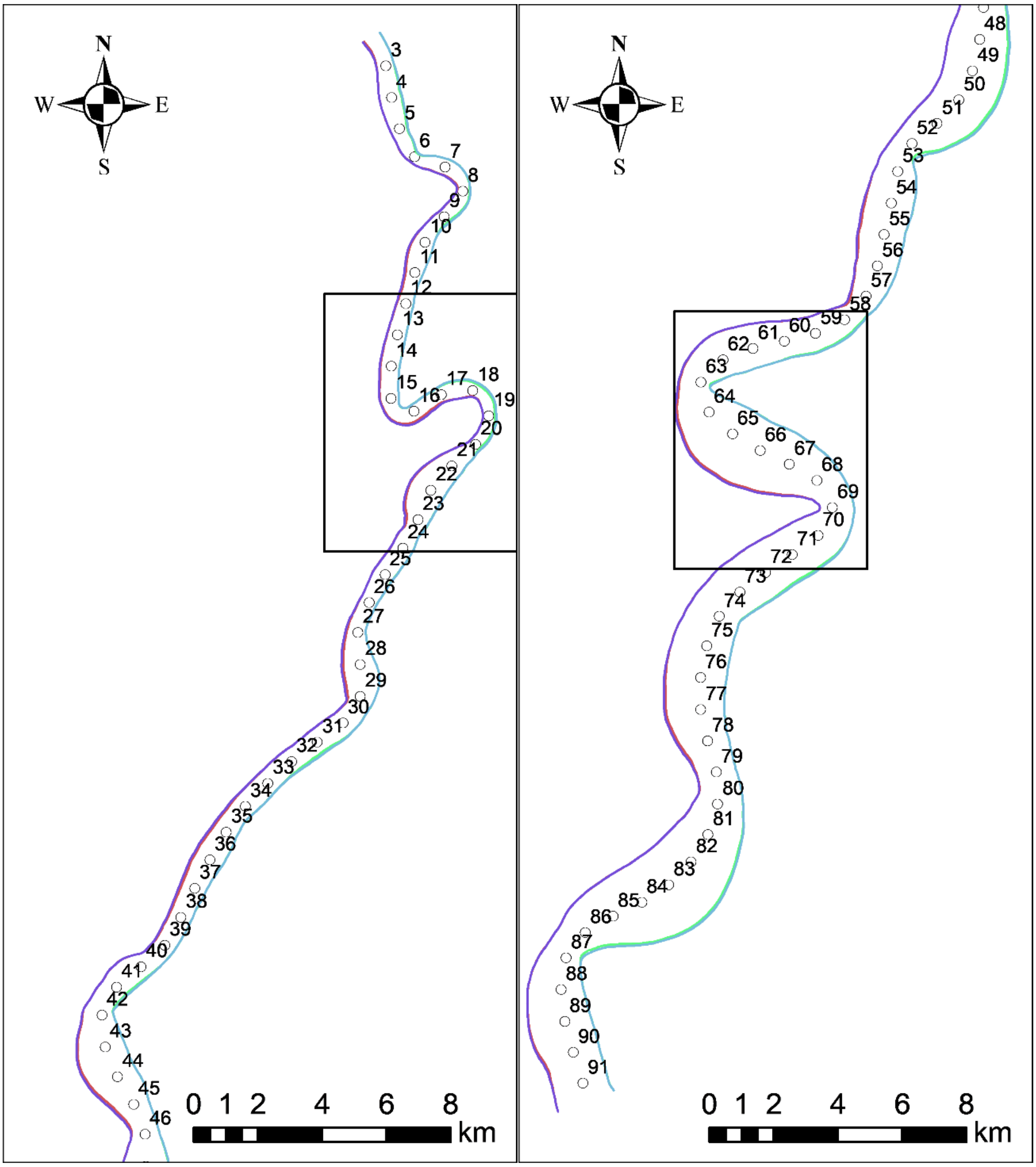

Figure 3-17 Simulated and observed bank lines starting from 2019 bank lines and bathymetry, simulating 2011-2019; i.e. this is not a real hindcast. Also showing the chainages (km). A zoom of the two local areas is shown in separate figures below to illustrate the bank line movement, which is difficult to see clearly at this scale. The numbers along the channel centre are the chainages used for longitudinal profiles.

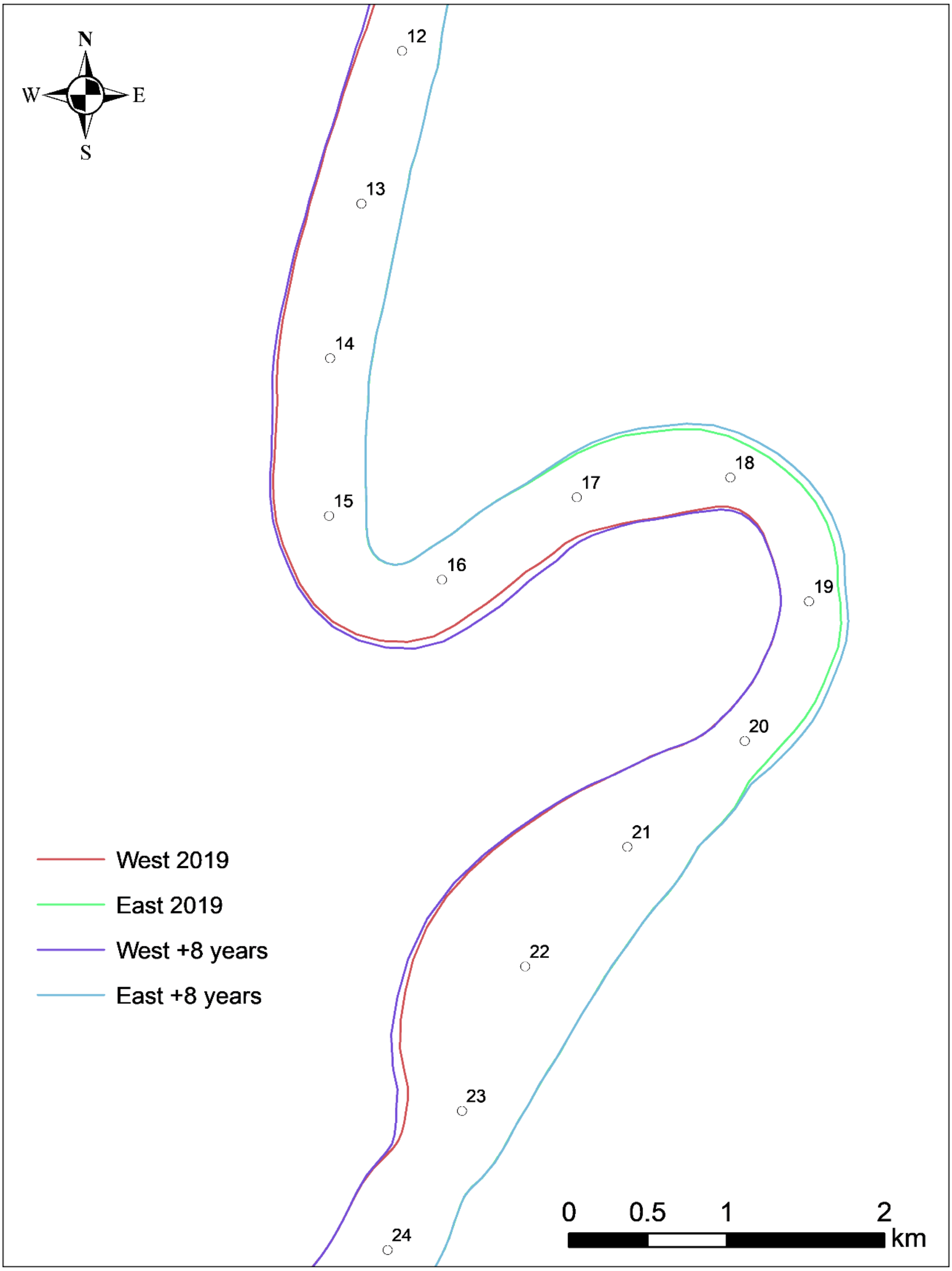

Figure 3-18 Bank line movement in a local area in the upstream end. The numbers along the channel centre are the chainages used for longitudinal profiles.

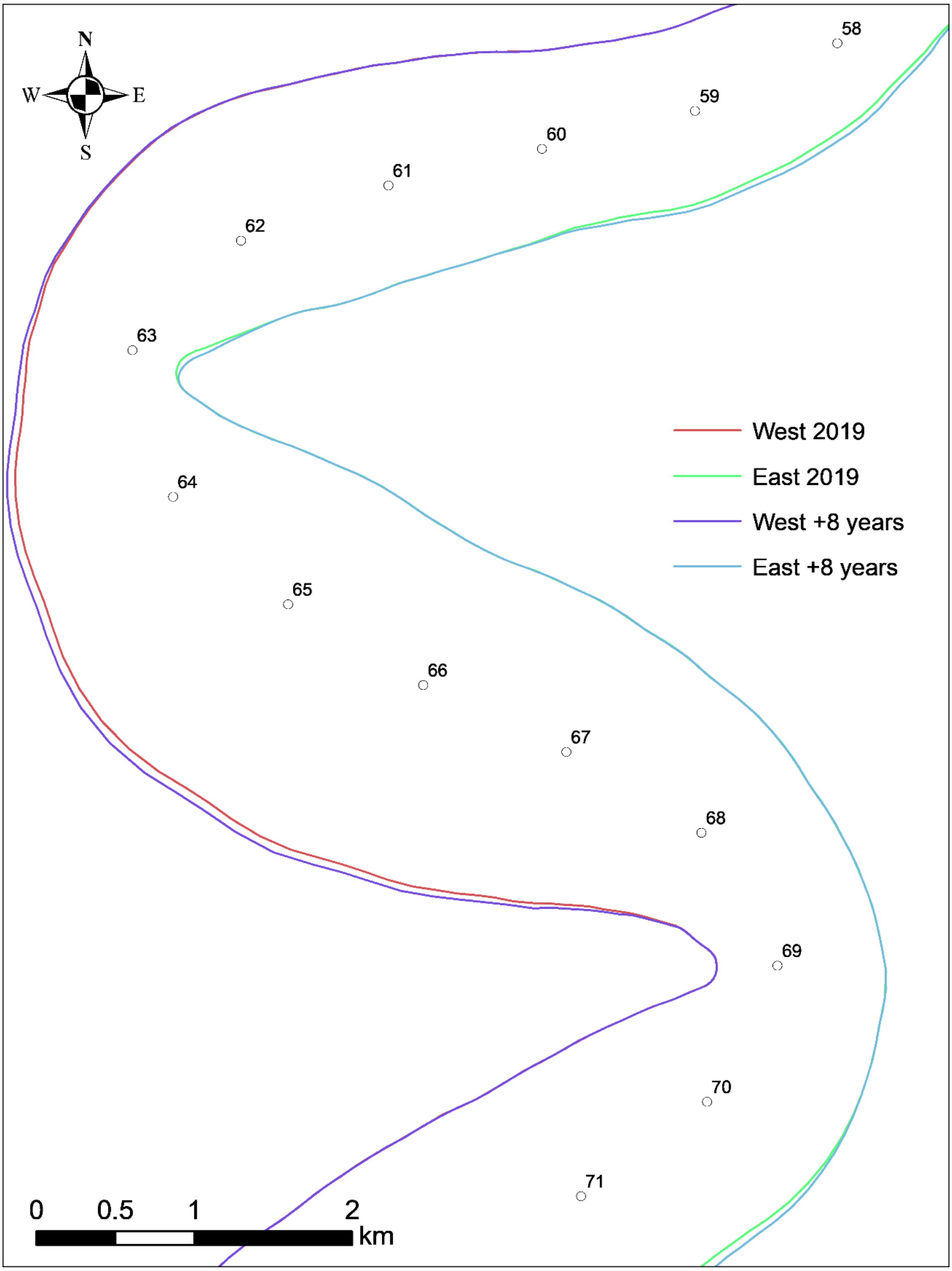

Figure 3-19 Bank line movement in a local area in the downstream end. The numbers along the channel centre are the chainages used for longitudinal profiles.

4 Model applications

The model applications are reported in this section.

4.1 Bank erosion forecast 30 years into the future

The existing and 30 years into the future boundary conditions were applied in conjunction to represent a reasonable time-series representing the next 30 years. Ideally, a continuous time-series should be available for the whole period to reflect the gradual increase in sea level and gradual lowering of the bathymetry due to subsidence. However, this is very cumbersome to do in the SWRM that provides boundary conditions for the Bishkhali model. Instead, the 30 years are covered by two simulations. The first simulation covers 15 years starting from the 2019 conditions (grid and bathymetry) using the existing 2019 boundary conditions generated by the SWRM. When this simulation is done, the results are processed into conditions representing 15 years into the future with subsidence representing 30 years into the future subtracted from the bathymetry. The second simulation uses that bathymetry and the associated grid as initial condition and runs 15 years using the future boundary conditions from the SWRM.

This is hence a stepwise approach in which the first 15 years represent existing conditions and the next 15 years represent conditions 30 years into the future.

Figure 4-1 shows the observed bathymetry from 2019 along with simulated future bathymetries from 2034 and 2049, noting that there was no 2011 bathymetry data from Bishkhali.

In the simulations, the Bishkhali River will in some cases not perform convincingly in the bends. With convincingly is meant that the anticipated behaviour is that the model sustains bars along the inner bends, although there is no law stating that this should be the case. However, if bars form along inner bends, the Bishkhali model can be seen to exhibit a tendency for some bars to erode, while some outer bends exhibit deposition. It is interesting to observe that the “hindcast” simulation running 2011-2019 starting from a 2019 bathymetry gave more convincing bars in the upstream end. A separate simulation was conducted for 2019-2035, which was submitted to the CEIP-1 Team Leader in 2021. That simulation showed good representation of the inner bars in the upstream end of Bishkhali, and the only significant difference between that simulation and the new 2019-2034 is the boundary conditions. Again, this underlines the importance of flow deflection from bars, which is a major weakness in Bishkhali due to the lack of two bathymetry datasets, bed samples and ADCP data. The Bishkhali model was developed using an alluvial resistance model to deflect flow from bars, but the model was not calibrated due to the lack of data.

One of the most important overall conclusions from the study is that flow deflection from bars is critical for the behaviour of the bathymetry and ultimately the planform, and all four models suffer from a lack of data to understand and describe the process in the model.

The interactions between planform, bathymetry and flow deflection also show how important is it to have data to reduce the uncertainties in the consequences of these interactions. The study suggests that eroding banks can change behaviour if the flow deflection is weakened.

It is also clear from the results that the longer bends with longer bars exhibit less sensitivity than the shorter bends. This behaviour makes sense considering that longer bends have the longer distance over which the flow resistance can work, and for shorter bends the water level gradient driving flow over the bar can be larger than for longer bends. This also suggests that shorter bends are less likely to be found in a silty river compared to a river with sand.

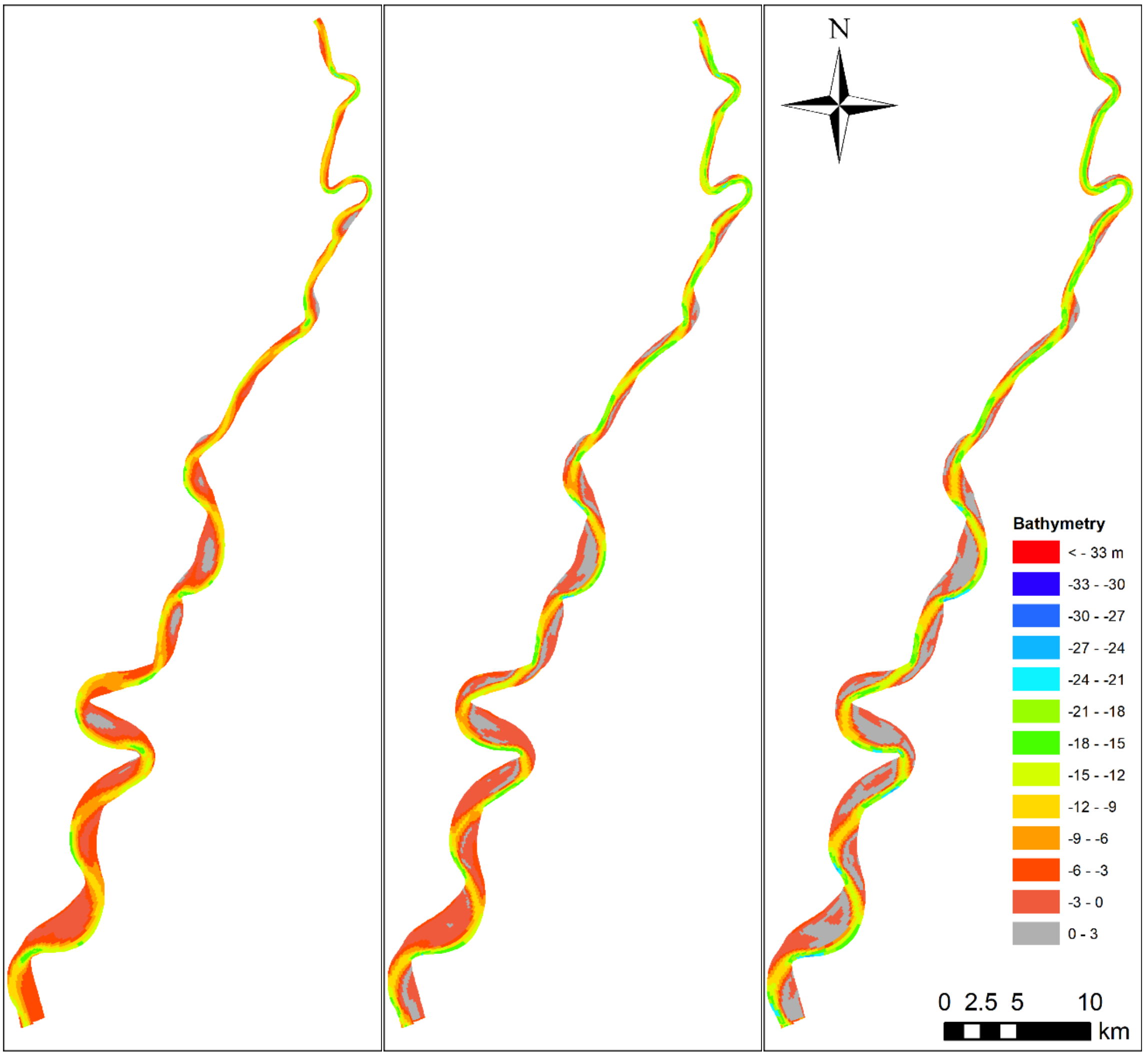

Figure 4-1 Bathymetries from various years. From left: 2011 (observed), 2019 (observed), 2034 (simulated), 2049 (simulated).

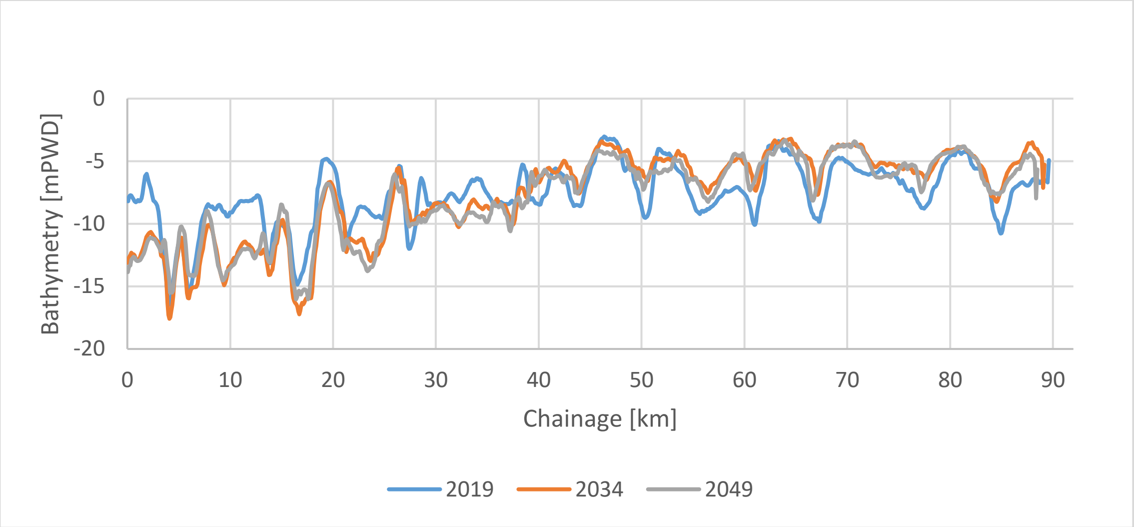

Figure 4-2 Width-integrated bed levels as a function of northing in the Bishkhali River for 2019 (observed), 2034 (simulated) and 2049 (simulated).

Figure 4-3 Bank lines 2019 (observed), 2034 (simulated), 2049 (simulated).

The width-integrated bed levels are shown in Figure 4-2. The results show that in the model, the Bishkhali will in the first 15 years exhibit general scouring in the upstream end and deposition in the downstream end. This process does not continue into the period 2034-2049 where the bed levels are similar. This forecast is unlikely to be correct since the Bishkhali model could not be calibrated with only the 2019 bathymetry available. Some model calibration was performed by using a low detail 2009 bathymetry, which suggested upstream scour and downstream sedimentation, but this calibration is uncertain. However, it is also manifested in the forecast for the future.

The general scour in the upstream end surely adds to the bank erosion problem, as increased depth in the upstream end reduces flow deflection from bars that need to be very shallow to cause flow deflection. This suggests that accurate calibration of the Bishkhali is necessary to achieve realistic bank erosion predictions.

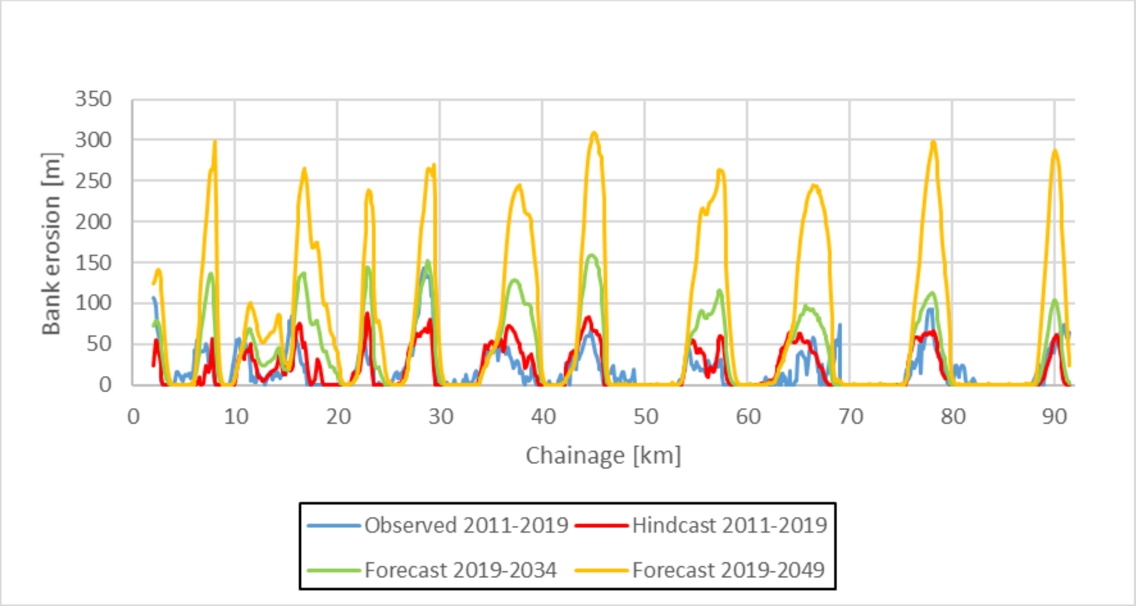

Figure 4-4 Bank erosion along the Bishkhali River west bank for 2011-2019, 2019-2034 and 2019-2049.

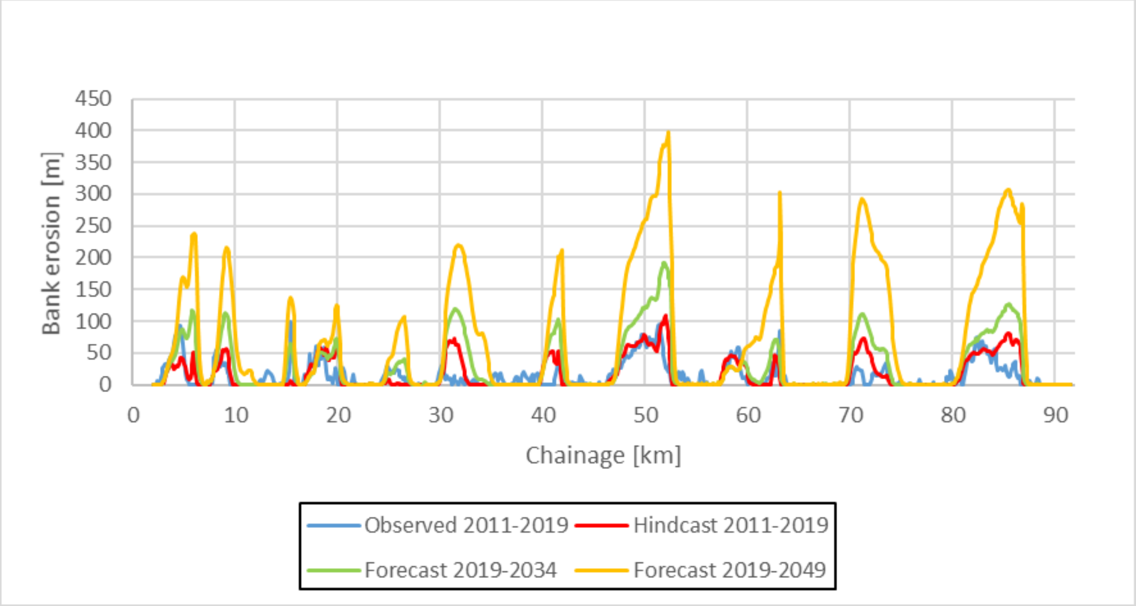

Figure 4-5 Bank erosion along the Bishkhali River east bank for 2011-2019, 2019-2034 and 2019-2049.

Figure 4-4 and Figure 4-5 show the simulated bank erosion as a function of the chainage along the river channel for reference compared to the 2011-2019 simulations and observations. It is noted that the 2011-2019 hindcast was carried out by starting from 2019 and running over 8 years, which was done because there was no 2011 bathymetry available.

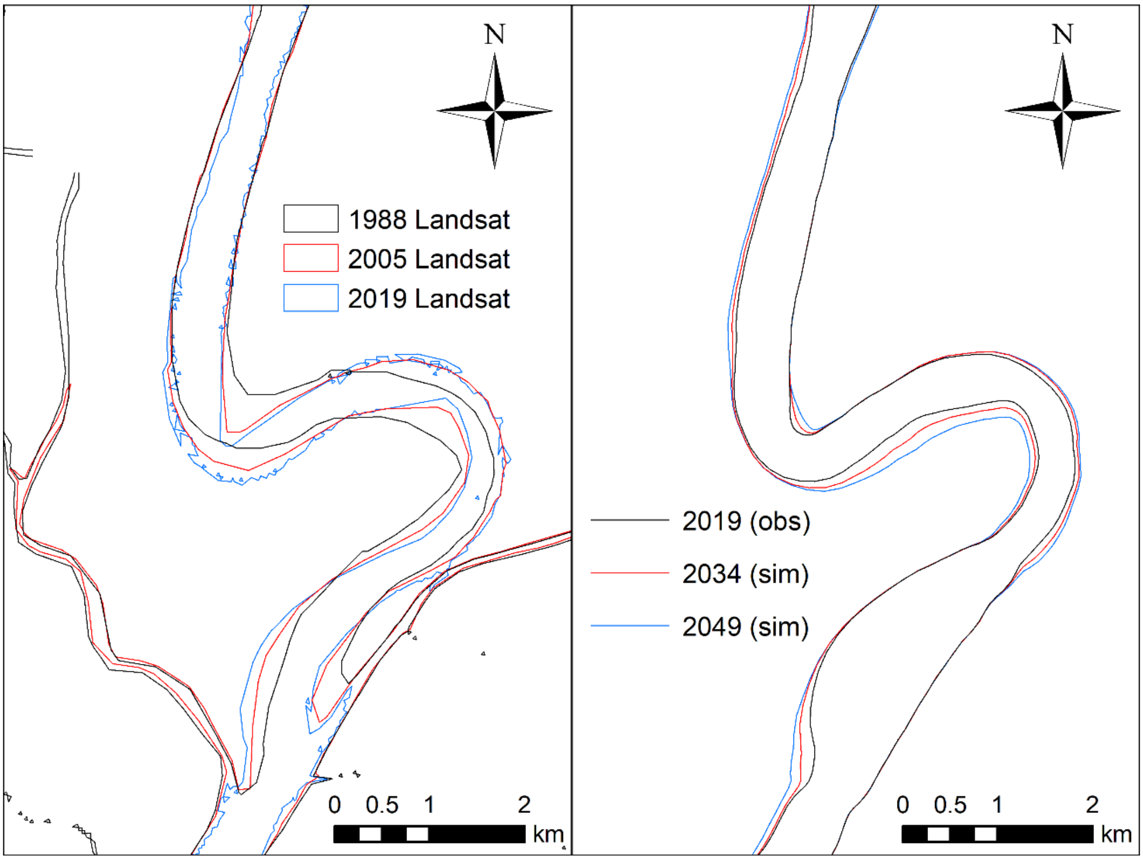

Figure 4-6 Comparison of bank lines digitized from Landsat 1988-2005-2019 and model results 2019-2034-2049. The bank lines hence cover comparable timescales and are shown in the very sharp bend in the upstream end of the Bishkhali River. The bank lines are drawn with the same colours over time to allow for direct comparison of the observations and model results, even though that should be done with caution.

Figure 4-6 shows a comparison of Landsat bank lines and model results for comparable timescales, namely Landsat 1988-2005-2019 and model results 2019-2034-2049. The purpose of the comparison is to illustrate the importance of bars in the bank erosion process. It is known from the model results that the upstream end exhibits some scouring, which could be true, but also has a large impact on the bank erosion process. Scouring means reduced bed levels leading to weakened flow deflection from bars, and in that particular bend the inner bar is so weakened in the forecast simulation that the erosion along the east bank is reduced and erosion along the west bank increased.

The simulated development is plausible but is ultimately sensitive to the bathymetry development. The Bishkhali model was never calibrated to bed level changes because only a 2019 bathymetry is available, and it is possible that the predicted scour will not take place.

The important conclusion that can be drawn from this is that bank erosion is sensitive to the bathymetry development. General scour leads to reduced bed levels, which will reduce flow deflection as flow deflection requires quite shallow flows over bars. Especially short bars lose the ability to deflect flow when the water depth over the bars grows.

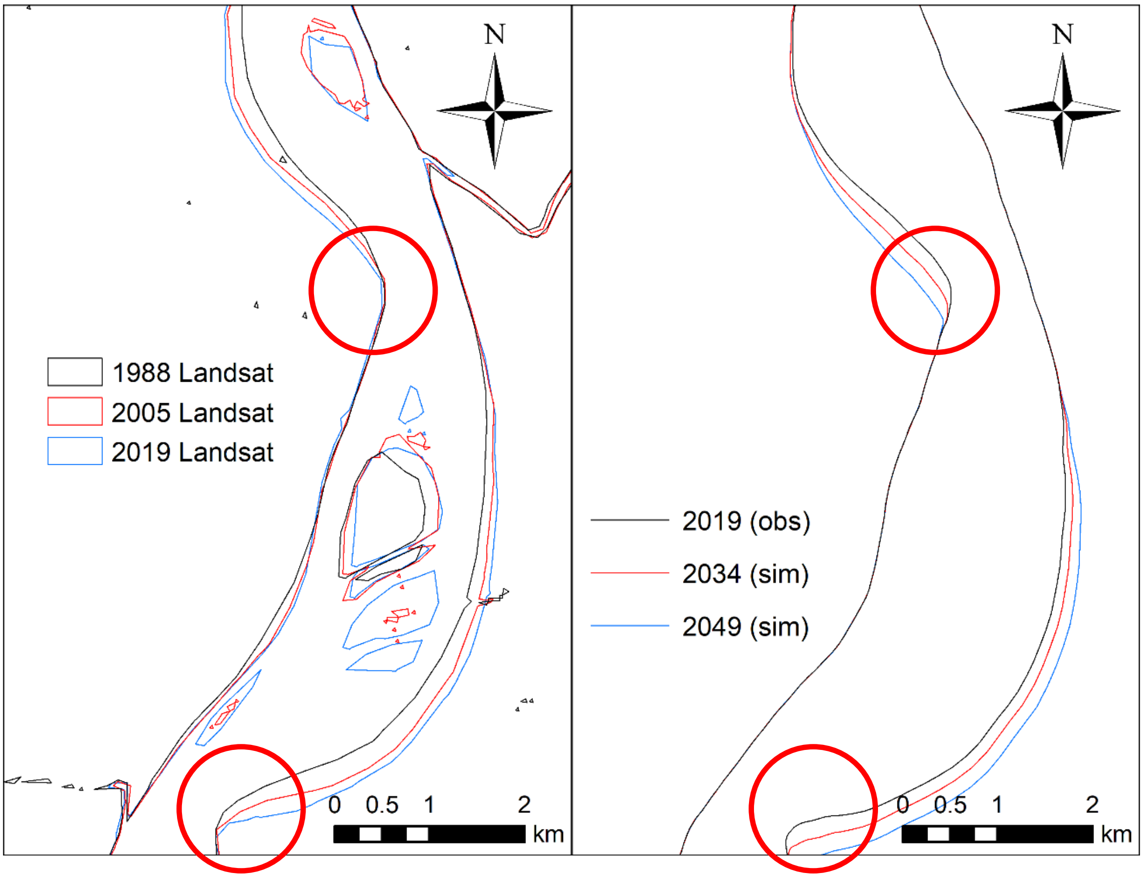

Figure 4-7 Comparison of bank lines digitized from Landsat 1988-2005-2019 and model results 2019-2034-2049. The bank lines hence cover comparable timescales and are shown in one of the large bends on the downstream end of the Bishkhali River. The bank lines are drawn with the same colours over time to allow for direct comparison of the observations and model results, even though that should be done with caution.

Figure 4-7 shows a comparison between Landsat and model forecast in a large bend further downstream. This comparison shows very good agreement between the historical bank lines and the forecasted bank lines, although this does not mean that the forecast is better at this location. In this area there is no general scour in the model.

When inspecting the results more carefully, the model tends to continue erosion too far downstream along each eroding bank (red circles in the figure). Again, this is related to flow deflection, which appears too weak in the model.

4.2 Impact of climate change on future bank erosion

The impact of climate change was quantified by running a 2034-2049 simulation starting from the same condition in 2034 with subsidence included but running 2034-2049 without climate change included in the boundary conditions.

Such a comparison is tricky due to the different grids, i.e. one cannot just take the difference between the bathymetries, which is a traditional approach when looking for differences between scenarios.

Alternative, the simulations can be conducted on static grids to make it easier to compare the results.

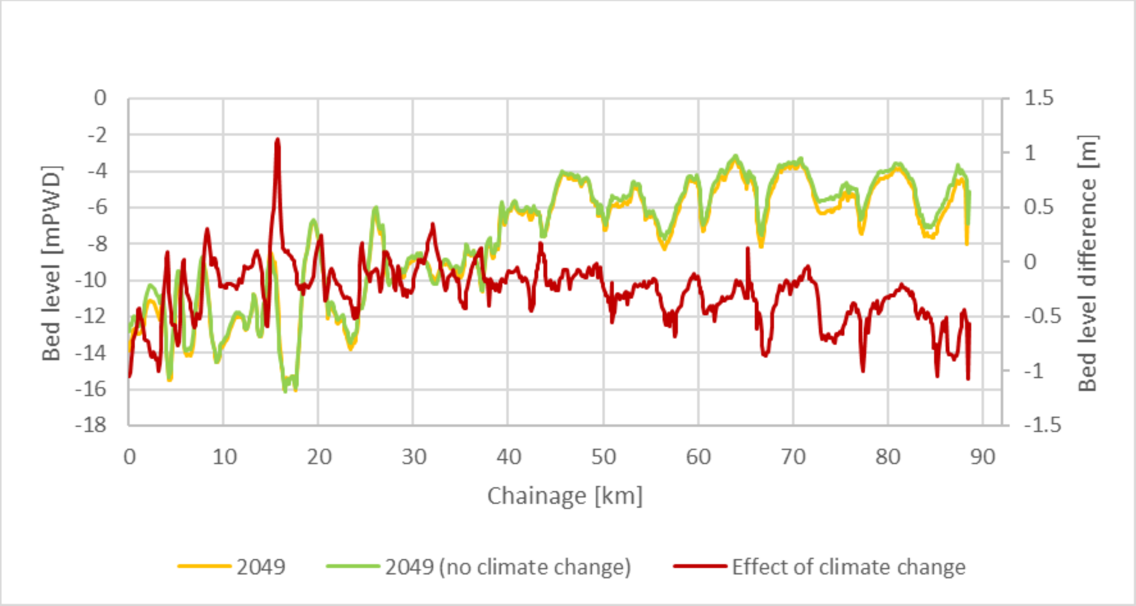

Figure 4-8 Width-integrated bed levels as a function of chainage in the Bishkhali River for 2049 with and without climate change (subsidence included in both simulations).

The width-integrated bed levels are shown in Figure 4-8. The differences between existing conditions and future conditions with climate change are small (subsidence is included in both 2049 results), but it can be observed that upstream bed levels with climate change are lowered 1 m in 2049 due to climate change, while the impact is smaller further downstream and largest downstream.

The explanation for this is sought in the boundary conditions. It is known that climate change increases the water levels in the downstream area and increases both ebb and flood tidal discharges and furthermore increases the net discharges during the monsoon.

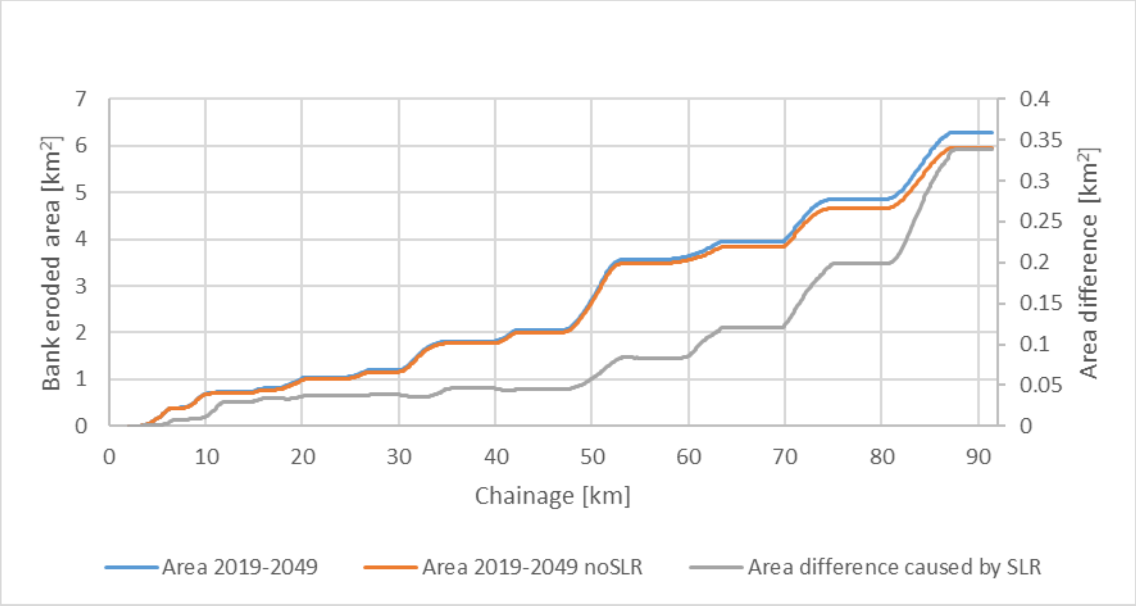

Figure 4-9 East bank eroded areas integrated along the river for the period 2019-2049 with and without climate change.

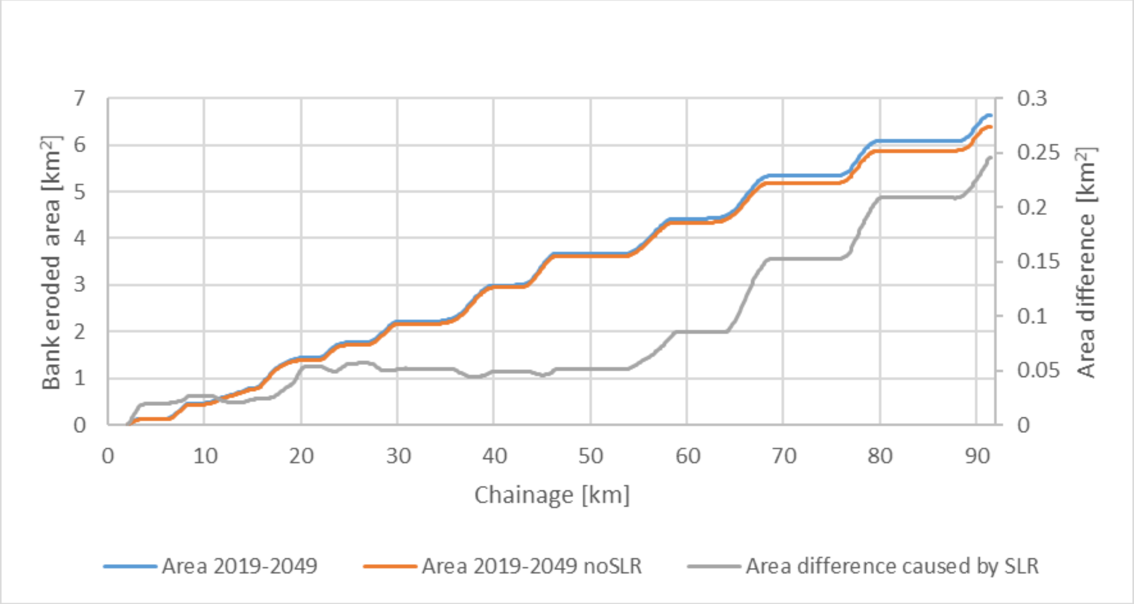

Figure 4-10 West bank eroded areas integrated along the river for the period 2019-2049 with and without climate change.

A clearer picture of the climate change impact on bank erosion is obtained by integrating the eroded areas along each bank, see Figure 4-9 and Figure 4-10. These show that climate change causes an increase in bank erosion, mainly in the downstream end. Climate change clearly causes increased bank erosion, and the reason is that the tidal discharges increase along the river. The integrated areas show that climate change causes the eroded area to increase by 4% along the western bank and 6% along the eastern bank.

The impact of climate change on bed levels in Bishkhali is not insignificant, while the impact on bank erosion is small. Though this sounds contradictory, the reason should be sought in the bank erosion formula, which can give the same erosion for a deeper channel if the deepening lowers the velocities.

4.3 Effect of bank protection on bed levels

The effect of bank protection on bed levels was tested by running alternative simulations covering the baseline period 2019-2034.

The simulations were conducted without updating the curvilinear grid to account for bank line movement, while the eroded material was included in the sediment budget. This is acceptable for shorter time-periods.

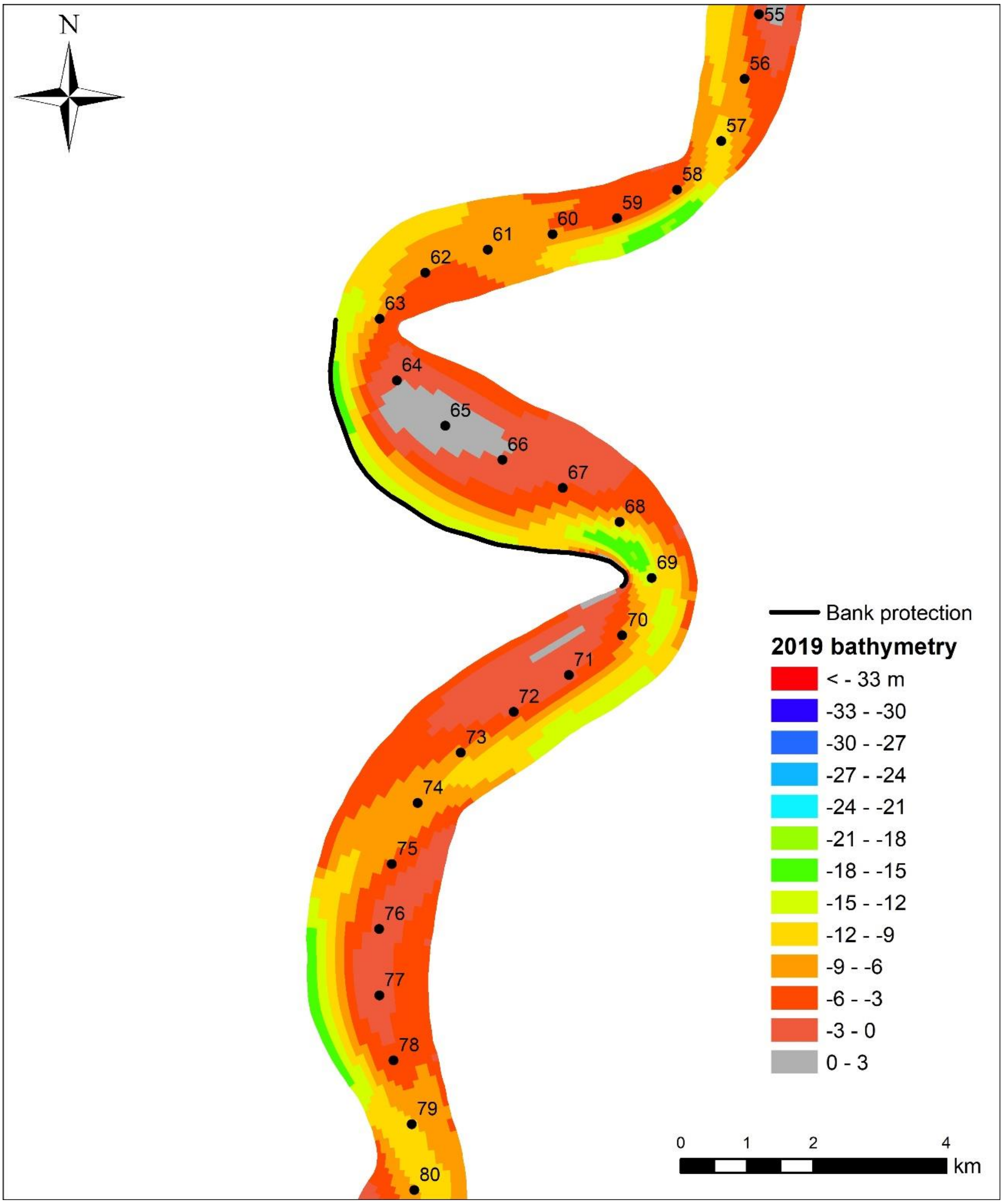

Figure 4-11 Protected bank along Bishkhali west bank.

Three simulations were conducted:

- 2019-2034 static grid (baseline)
- 2019-2034 static grid no bank erosion
- 2019-2034 static grid protect one bank

The bank-eroded material is important for the sediment budget, but the composition of the material is not known.

Figure 4-11 shows the bank in the very sharp bend in the downstream end, which is protected as the only bank in a scenario.

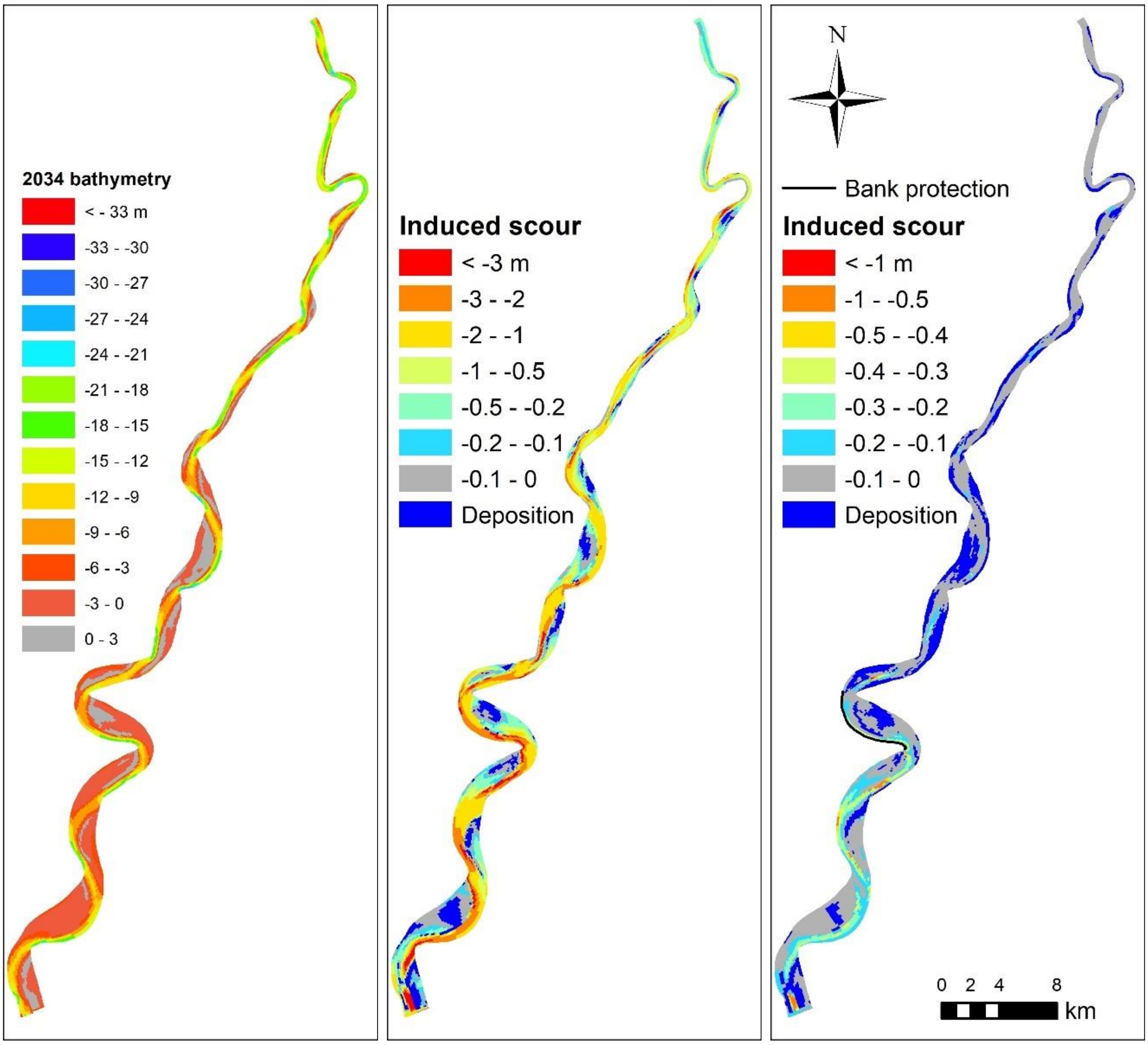

Figure 4-12 Simulated 2034 bathymetry (left) and induced scour 2019-2034 caused by no bank erosion (middle) and protection of one bank (right).

Figure 4-12 shows the simulated 2034 bathymetry for existing conditions (bank erosion calculated and included, but with a static grid) as well as the simulated induced erosion for the period 2019-2034 caused by the two scenarios with no bank erosion and one bank protected. Note that all three figures have different colour scales.

With all banks protected from erosion, the bed levels in all deep channels will be reduced, while bars tend to grow higher. Protecting just one bank from erosion generates a similar response, but smaller and more localized and moving downstream.

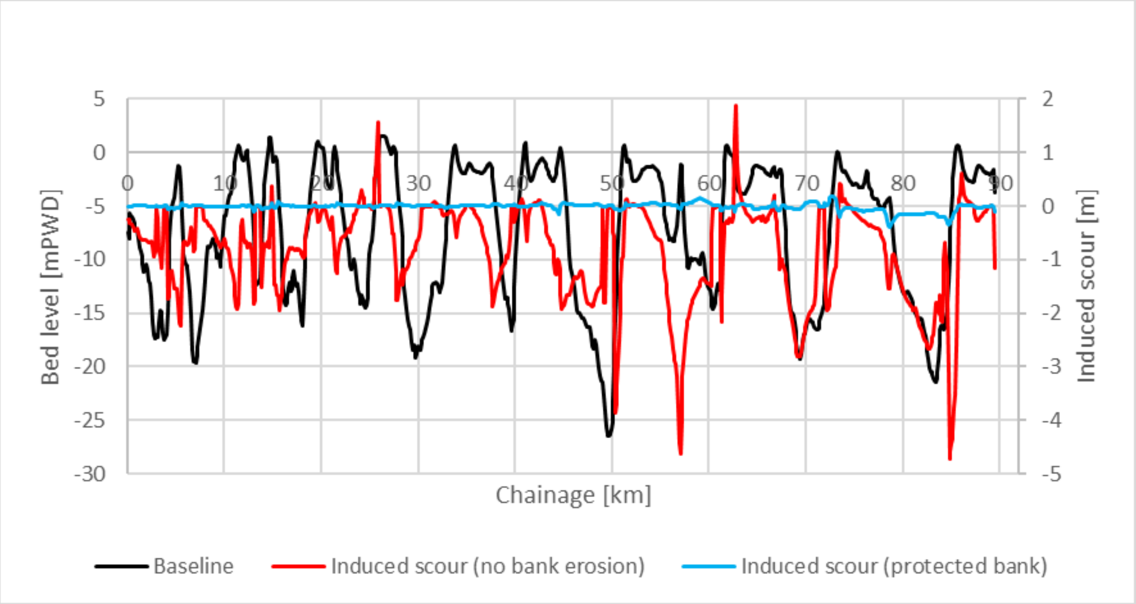

Figure 4-13 Simulated bed levels along eastern bank in 2034 for existing conditions, no bank erosion and one protected bank.

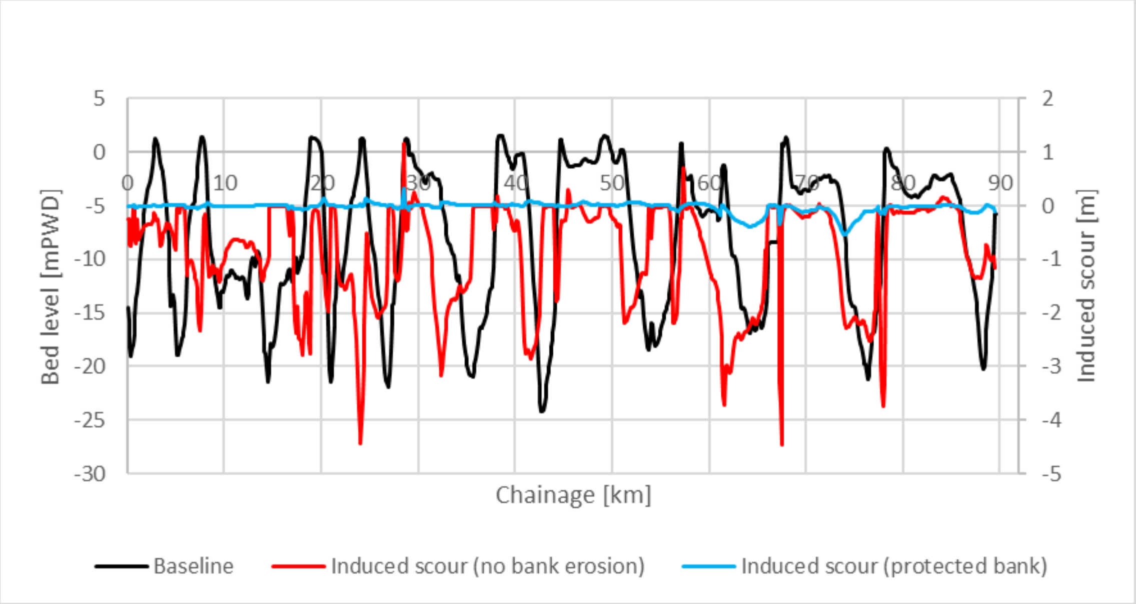

Figure 4-14 Simulated bed levels along western bank in 2034 for existing conditions, no bank erosion and one protected bank.

The bed levels and induced scour along the banks are shown in Figure 4-13 and Figure 4-14. The results show that the bank protection generally lowers bed levels in the deep channels. The extreme case where all banks are protected from erosion will lead to bed levels reduced by up to 4 m in the deep channels, while the case with one bank protected will only reduce local bed levels by around 0.5 m.

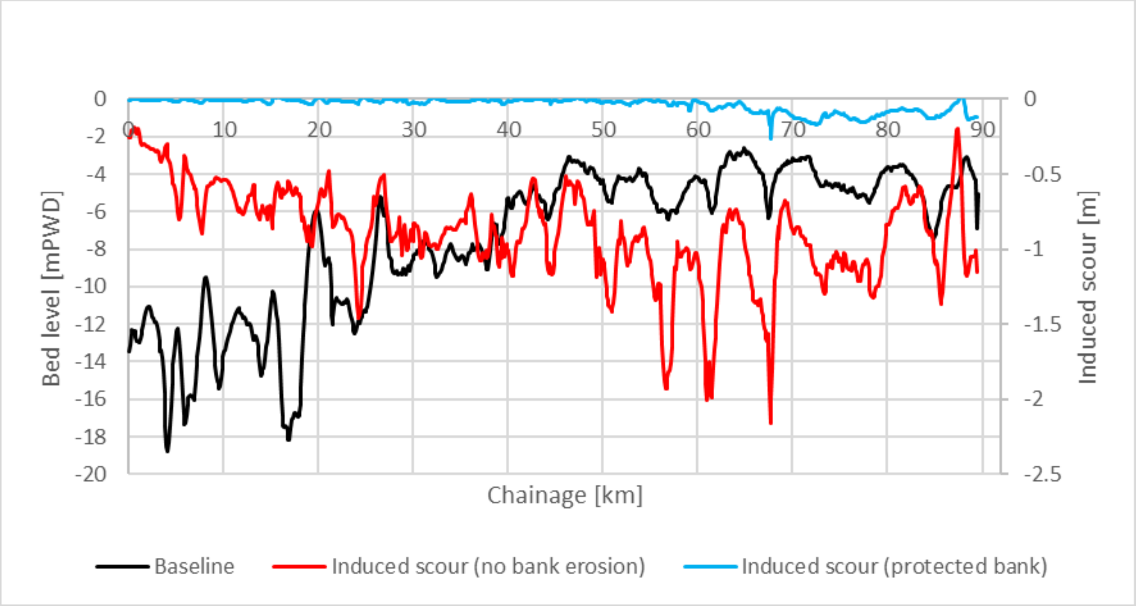

Figure 4-15 Simulated width-integrated bed levels in 2034 for existing conditions, no bank erosion and one protected bank.

The width-integrated bed levels in Figure 4-15 show that the bank material plays a significant role in the sediment budget, and protection of all banks from erosion will generate reduced bed levels from upstream to downstream, increasing the magnitude in the downstream direction. Bed levels are up to 2 m lower. For just one bank protected the impact is qualitatively the same, but with a much smaller magnitude.

The impact of protecting the single bank on other eroding banks was also investigated based on the simulation results. For Bishkhali it was found that the impact on other banks is very small, which is difficult to show graphically. The impact was typically around 2 m increased erosion compared to around 100 m erosion for existing condition, so a slight increase in bank erosion downstream of the protected bank. The increased tidal flow associated with induced scour is probably the most important reason why the bank erosion increases slightly.

The most important aspect of bank protection is not that it leads to slightly increased bank erosion downstream. The most important aspect is that it leads to reduced bed levels along the eroding banks, which must be considered for bank protection design.

5 Conclusions

The present report documents the development of the MIKE 21C model of the Bishkhali River.

There were two bathymetry datasets for the Bishkhali River, namely 2009 and 2019. The 2009 data is too sparse for 2D contouring, so only the 2019 bathymetry was used in the 2D model development. However, the 2009 bathymetry data is valuable if used correctly, simply because it is the only older bathymetry dataset. The value of the 2009 bathymetry dataset was carefully brought into the model development process by determining its integrated bulk volume curve in a manner where the 2019 bathymetry resolution was brought down to the level of the 2009 bathymetry survey. By doing this, it was possible to extract observed sedimentation 2009-2019 in the shape of an integrated bulk volume curve (longitudinal), while 2D comparison was not feasible.

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

There are three sediment bed samples in the Bishkhali River, which would be enough if the samples showed uniform sediment (single fraction). However, the bed samples show that the sediment is a mix of sand and silt, and with just three bed samples, a meaningful spatial distribution of the sediment fractions cannot be determined. It is a given that the sand is generally found on bars (the sample labelled CL is located on the side slope of a large bar), while the deep channels are silty, but it is likely that there is a longitudinal variation, which cannot be determined without using a lot more bed samples.

Suspended sediment samples are available for 2016 and 2019. There is no particle size distribution data for the suspended sediment, and there is no data at the upstream end, which would be helpful for establishing an upstream boundary condition.

Historical bank lines were digitised from Landsat images 1988-2019. These showed very consistent and systematic bank erosion, typically 5-10 m/year, and most of the time the same banks erode. The observed bank erosion correlates extremely well with the bed levels, such that almost all bank erosion takes place along outer bends with deep bend scour.

There is no information about the sediment size distribution in the riverbanks. It is known from the observed bank erosion that – assuming the banks are not all clay – the bank material is a significant contribution to the sediment budget. Hence, the lack of particle size distribution data in the banks is a significant source of error.

The grid (800x15 cells) was based on the 2019 bank lines digitised from the 2019 Landsat image. While the other three rivers (Sibsa, Pussur, Baleswar) had two separate MIKE 21C models constructed based on the 2011 and 2019 bathymetries and bank lines, there was only one bathymetry (2019) for the Bishkhali River, and hence only one (2019) model could be developed. This will not change anything in terms of model application, as all scenarios are expected to start from the 2019 grid and bathymetry.

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 and downstream water level time-series.

The sediment model was formulated as a 2-fraction model with sand and silt. Clay was omitted because it is hardly found in the bed samples, and hence it was concluded that the clay was morphologically unimportant even if it contributes significantly to the sediment concentrations. The silt was simulated using the exact same cohesive model parameters used for the other three models (Sibsa, Pussur, Baleswar), which was shown to validate well against observed concentrations, but more importantly the erosion model has been validated to observed bed level changes in those models. The sand was treated as a non-cohesive fraction using Garcia & Parker (1991) suspended sediment transport formula, which could not be validated.

Observed suspended sediment concentrations were assumed to contain significant amounts of clay, and it was observed that the “inherited” cohesive sediment parameters lead to lower concentrations compared to observations, which is also to be expected if the observations contain a large (unknown) clay fraction.

A morphological “hindcast” was performed for 2011-2019. The simulated bulk volume curve matches reasonably with the 2009-2019 observed bulk volume curve (uncertain). Bank erosion is a significant contribution to the sediment budget in terms of bed level changes, but very small compared to the sediment transport.

Bank erosion was simulated using the same formula with 50% increased rate compared to the coefficients that were used for Sibsa and Baleswar (Pussur River has slightly different critical depth parameter). Bishkhali River is located further east compared to the more tidal rivers (Sibsa, Pussur, Baleswar) and is hence closer to the Lower Meghna, and more pronounced monsoon flow is observed in Bishkhali River relative to the tidal flow. The sandier river and relatively stronger monsoon signal suggest that Bishkhali River should have the higher bank erosion rates that are also observed. The bank erosion prediction aligns very well with the observations.

5.1 Recommended future data collection

The data for the Bishkhali River is insufficient for the development of a well calibrated morphological model for the following reasons:

- Only one good resolution bathymetry (2019)
- Too few bed samples (3)
- No particle size distribution for the suspended sediment
- No particle size distribution for the bank material

Having only one bathymetry is always problematic because it is difficult to hindcast in detail a morphological development, which is the best way to calibrate such models. This is not a circumventable shortcoming; Bishkhali River only has one more bathymetry dataset (2009) in addition to what was obtained for the project, and the 2009 bathymetry was too coarse for 2D contours. While the other rivers, such as Sibsa River, Pussur River and Baleswar River, were subjected to the very good resolution bathymetries of the GRRP project in 2011, Bishkhali River did not have the same survey, so the relatively coarse 2009 bathymetry is the only older bathymetry compared to 2019.

- It is recommended to collect a bathymetry within a reasonable time frame

There are too few bed samples to determine a meaningful bed surface distribution. Especially the longitudinal variation is essentially unknown, and it is likely that there are large differences from upstream to downstream.

- Many more bed samples should be collected for the Bishkhali River.

There is no information available for the particle size distribution data in the suspended sediment samples, and there are no suspended sediment samples in the upstream end.

- Suspended sediment concentration data should be collected at the upstream and downstream ends.
- Particle size distributions should be determined for all suspended sediment samples.

There is no information available for the particle size distribution data in the bank material, which is a significant contributor to the volume changes in the river:

- Several bank material samples should be collected along the Bishkhali River with both longitudinal and vertical samples. These samples should be subjected to particle size distribution analysis as well as density, as the banks are more compacted than the riverbed (especially in terms of cohesive sediment in the banks).

5.2 Recommended model improvements

The model development had a lot of focus on the bends to get a good representation of bars, which is critically important for getting good predictions of bank erosion.

The current version of the Bishkhali River model opens for some questions about individual model components. Flow deflection from bars is not known in detail, and due to dunes, it could be much stronger compared to what is currently modelled. In the present version of the model, the bars only weakly deflect flow, which was shown to be essential for the model behaviour, but the effect is likely to be stronger.

There is a lot of uncertainty with respect to the sediment regime in the river. The river has been modelled as mixed mud and sand, but the spatial distribution between mud and sand as well as the distribution in the sediment inflows are largely unknown. The very sharp bends suggest that the bars are generally sandy with flow conditions leading to dune formation, which was also shown to be the case for the Pussur River model. Hence, it is likely that a dune description will be necessary for the Bishkhali River model.

Measured velocity profiles are essential for the improvement of the model. Without measured velocity profiles, the unique calibration of the model in terms of flow resistance and sediment transport cannot be identified. Without measured velocity profiles, the model will have a range of calibrations.

Model improvements require more data.

5.3 Conclusions from the scenario simulations

The developed model was applied for the following scenario simulations:

- Bank erosion projection 30 years into the future
- Impact of climate change 30 years into the future
- Impact of bank protection on bed levels

Bank projection 30 years into the future showed no qualitative changes to the river bathymetry. However, future bar formation and locations are sensitive to the flow resistance formulation, which is a general conclusion for all the developed models. For the Bishkhali it is also observed that bar formation is sensitive to the upstream sediment inflow. This is manifested in general lowering of bed levels due to reduced upstream sediment inflow, which causes bars to deflect flow less than they do in more shallow conditions.

Bank erosion patterns are predicted to be generally unchanged in the future. In the upstream end, the results are sensitive to bar formation, but the upstream end is also characterized by no polders, so this sensitivity is less important.

The differences between existing conditions and future conditions with climate change are small, but it can be observed that upstream bed levels with climate change are lowered 1 m in 2049 due to climate change, while the impact is smaller further downstream and largest downstream.

Climate change causes an increase in bank erosion, mainly in the downstream end, and the reason is that the tidal discharges increase along the river. The integrated areas show that climate change causes the eroded area to increase by 4% along the western bank and 6% along the eastern bank.

The impact of protecting the single bank on other eroding banks was also investigated based on the simulation results. For Bishkhali it was found that the impact on other banks is very small, which is difficult to show graphically. The impact was typically around 2 m of increased erosion compared to around 100 m erosion for existing condition, so a slight increase in bank erosion downstream of the protected bank. The increased tidal flow associated with induced scour is probably the biggest reason why the bank erosion increases slightly.

The most important aspect of bank protection is not that it leads to slightly increased bank erosion downstream. The most important aspect is that it leads to reduced bed levels along the eroding banks, which must be considered for bank protection design. The results show that the bank protection generally lowers the bed levels in the deep channels. The extreme case where all banks are protected from erosion will lead to bed levels reduced by up to 4 m in the deep channels, while the case with one bank protected will only reduce local bed levels by around 0.5 m.

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