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)

Sangu 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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Memo No: CEIP/LTMRA/0622/169 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 Sangu 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 ***"Sangu 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
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ACRONYMS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
BDP2100	Bangladesh Delta Plan 2100
BIWTA	Bangladesh Inland Water Transport Authority
BMD	Bangladesh Meteorological Department
BoB	Bay of Bengal
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).

<u>The value of Landsat data in Bangladesh</u>
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.

<u>Model development template</u>
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.

Model applications
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.

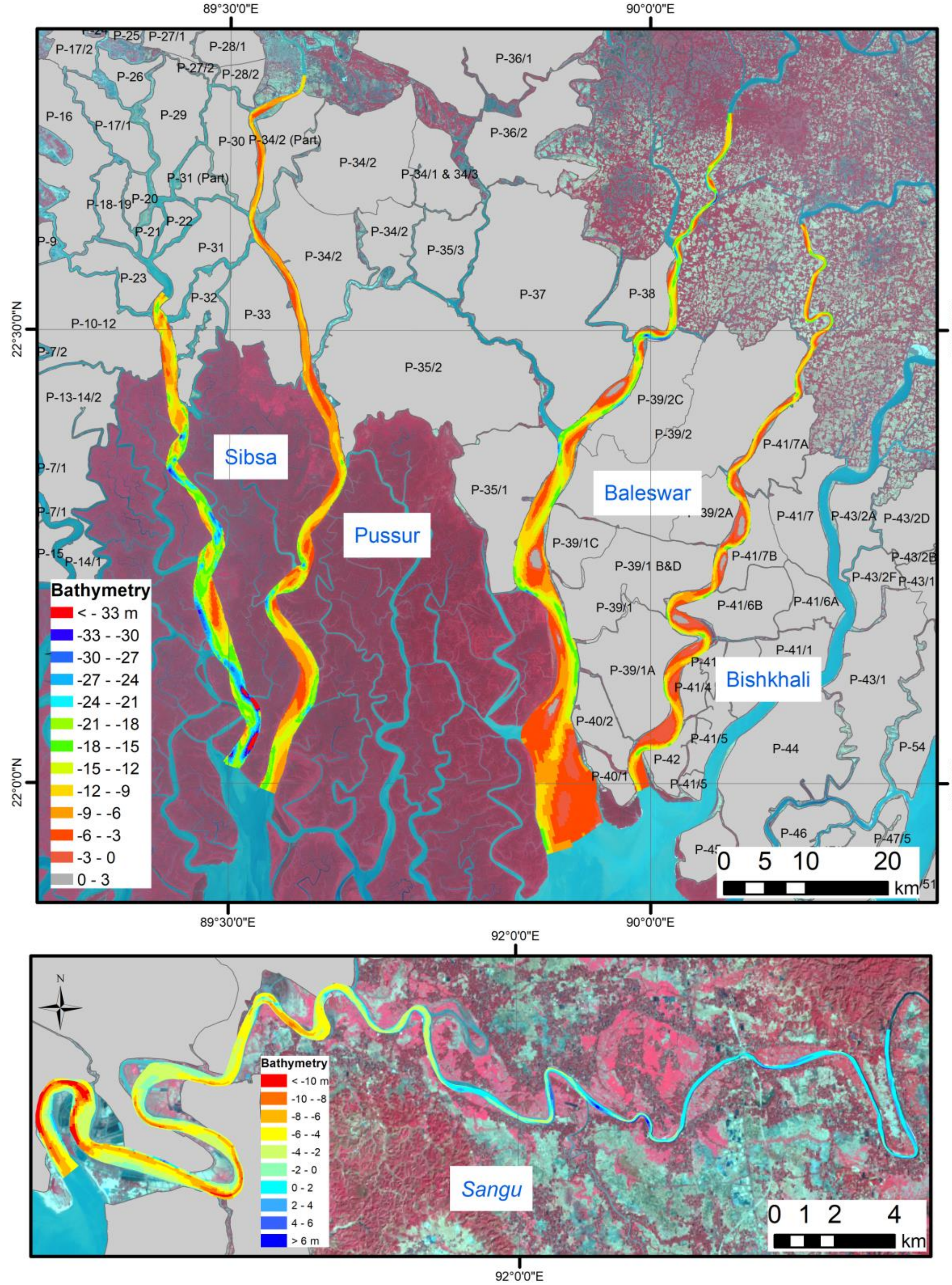

Figure 1-2 The five MIKE 21C models developed for the project.

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. Such data was converted to BTM and mPWD.

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

The MIKE 21C models are very long, and to avoid narrow graphics, some 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 Sangu River 2D maps shown next to each other are useful for showing several results together because they belong together. Examples include time-series of 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, the fact that the Sangu River runs almost north to south makes it convenient to use the BTM northing as coordinate in the graphics. This cannot be done for all MIKE 21C models (e.g. Baleswar River has a sharp bend where the northing coordinate hardly changes over some kilometres). For models, where the BTM northing cannot be used as unique longitudinal coordinate, a chainage coordinate was applied.

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

In this section we document all the data that was used for the model development. The projection is BTM, and the vertical datum is mPWD.

2.1 Bathymetry

The river system has been surveyed in previous years, so suitable bathymetry information was readily available. A bathymetry survey was conducted in 2005 for the Sangu River from "Hydrological Assessment for Proposed Urea-Ammonia Plant in Bangladesh" project, IWM (2005). A more detailed bathymetry survey was conducted by IWM for another project "Feasibility study for restoration of dry season flow through dredging in the Sangu, Matamuhuri and Kornofuli river for improvement of navigability, domestic water use and irrigation" for BIWTA, IWM (2018), and in 2020 a more extensive survey is done for project "Feasibility Study for Restoration of Sangu and Matamuhuri River Basin" for BWDB. The bathymetric survey transect has been shown in Figure 2-1 for 2005, in Figure 2-2 for 2018 and in Figure 2-3 for 2020. Some surveyed cross-sections of Sangu River are presented in Figure 2-4 and contoured bathymetry for 2018 and 2020 is shown in Figure 2-5. Cross-sections surveyed under the study are compared with those data to assess the morphological conditions prevailing in the study area.

Table 2-1 Available bathymetry data for Sangu River.

Sl.	River	Survey Year	Extent	Remarks	Source
1	Sangu	August 2020	From Thanchi to Coast	180km @ 500m interval	IWM (Sangu & Matamuhuri feasibility study)
2	Sangu	January 2018	From Bandarban to Coast	About 95km @ 500m interval	IWM (3 route)
3	Sangu	2005 (July-August)	From Dohazari to Coast	About 50 km @ varying intervals	IWM (Hydrological Assessment for Proposed Urea-Ammonia Plant in Bangladesh)

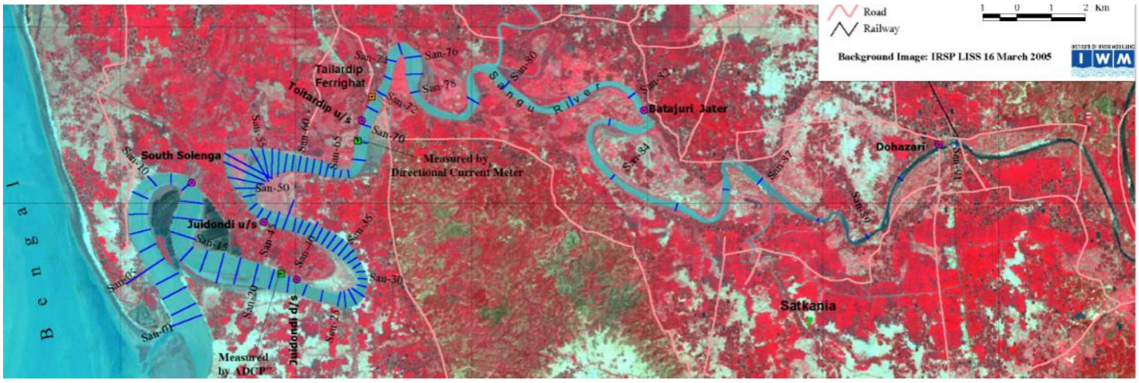

Figure 2-1 Bathymetric measured cross sections 2005 for Sangu River.

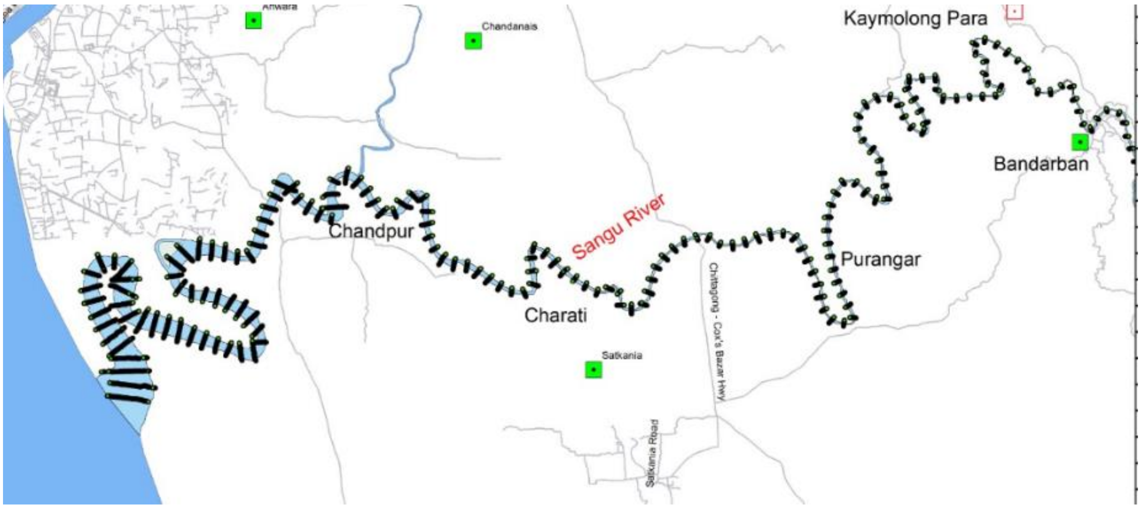

Figure 2-2 Bathymetric measured cross sections 2018 for Sangu River.

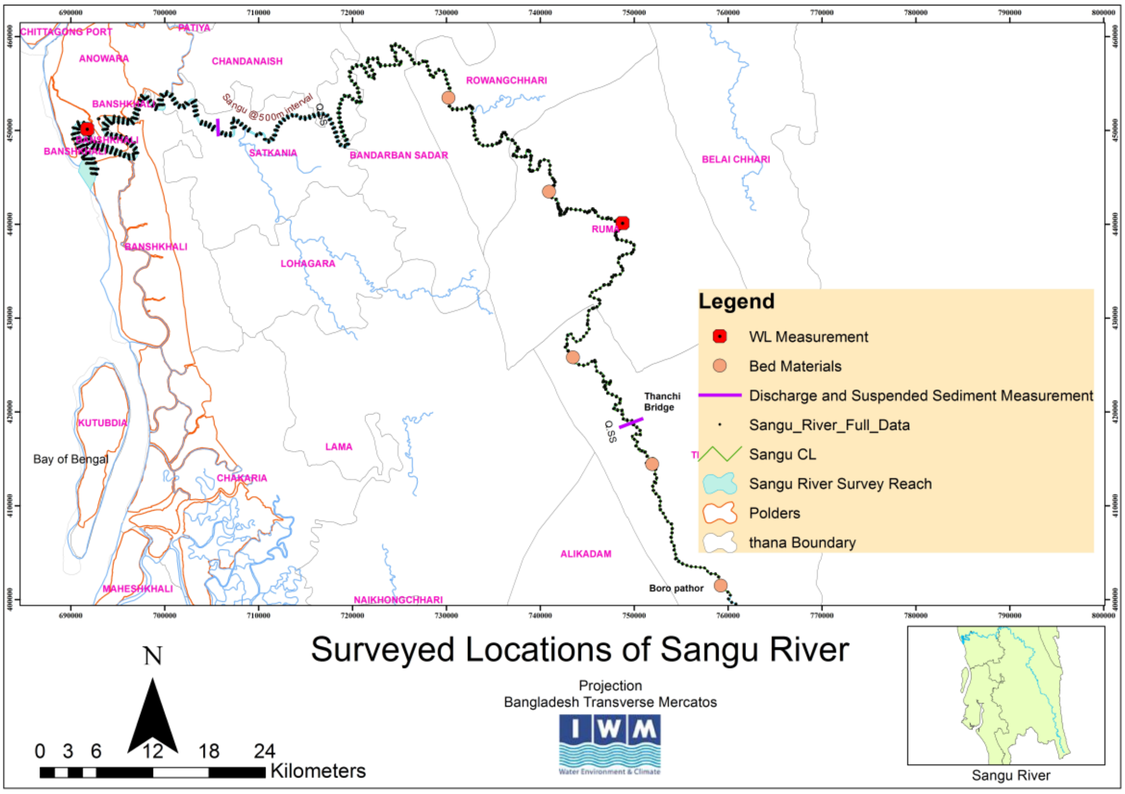

Figure 2-3 Bathymetric measured cross sections 2020 for Sangu River.

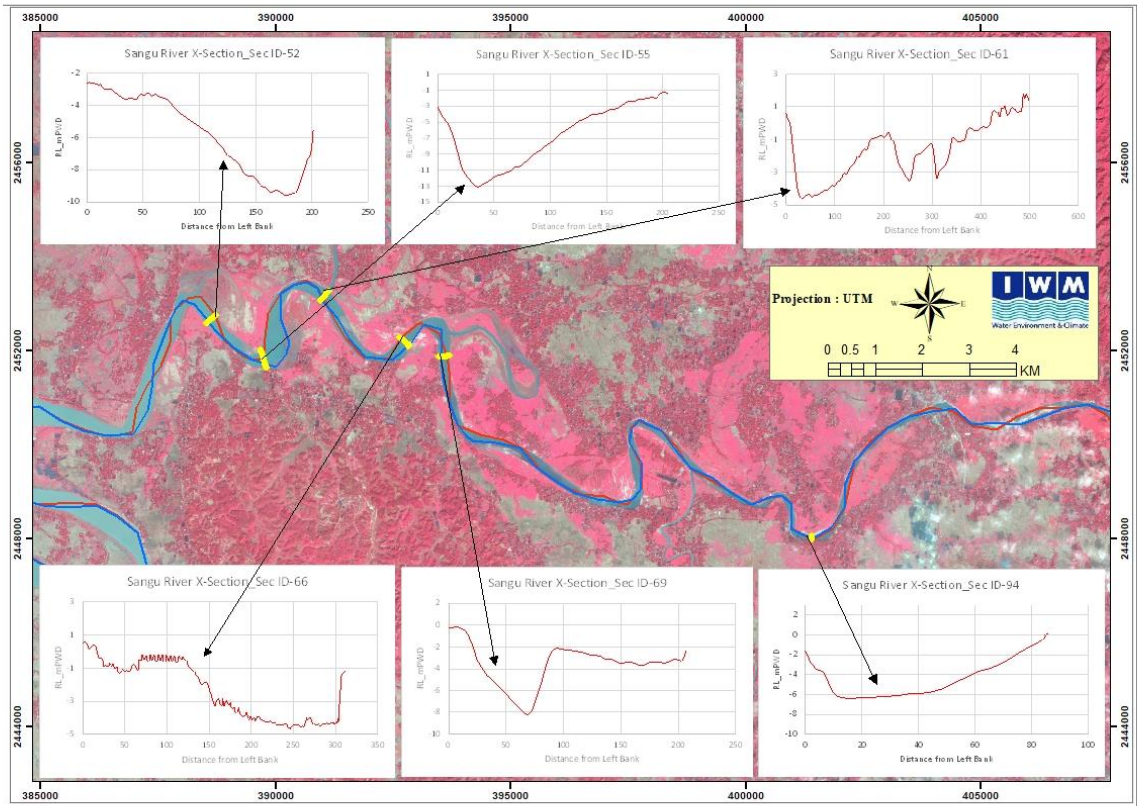

Figure 2-4 Cross-sections of Sangu River (2020).

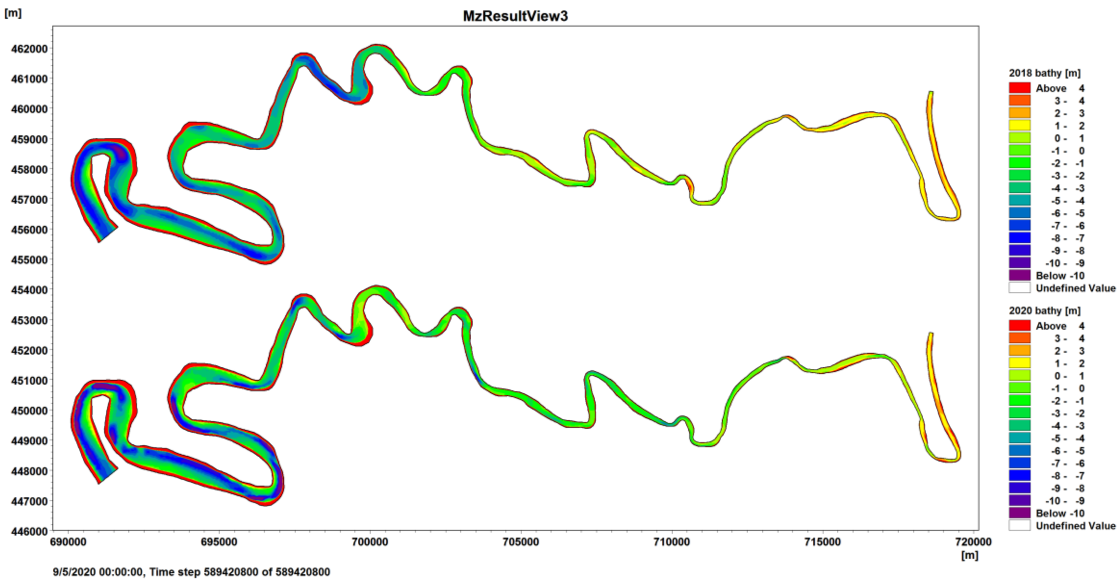

Figure 2-5 Contoured bathymetries 2018 (top panel) and 2020 (bottom panel).

The cross-sections of the Sangu River surveyed in the year 2020 have been compared with previous cross-section data available in the IWM archive which was surveyed in 2018. The cross-sections of the same locations in Sangu River, surveyed in 2018 and 2020, have been compared and are presented in Figure 2-6. Cross-section comparison shows the morphological change that has taken place in these study rivers within this period.

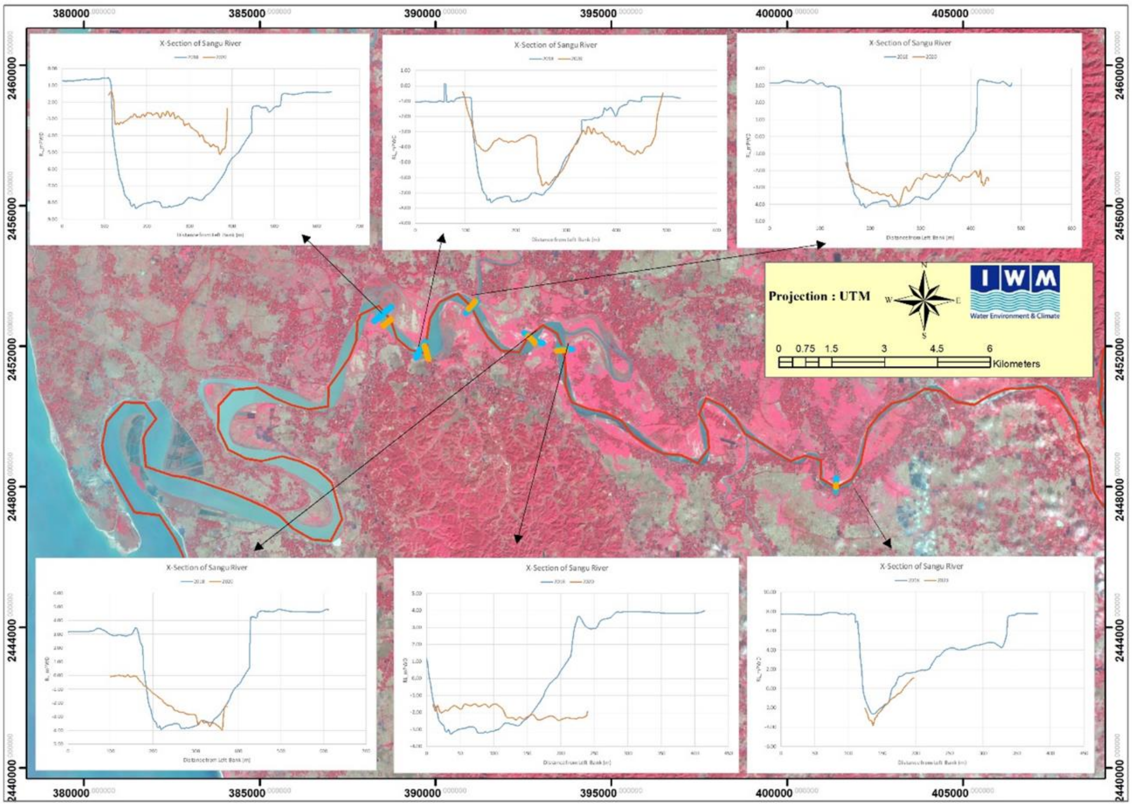

Figure 2-6 Comparison of selected cross-section profiles of the Sangu River (2020 and 2018).

2.2 Water level time-series

Table 2-2 shows the water level data along with dates for the available stations. BWDB has stations in Banigram, Dohazari and Bandarban. The stations are shown in Figure 2-7 and Figure 2-8.

Table 2-2 Water level data for Sangu River.

Sl.	Location	From Date	To Date	River	Source
1	Dohazari	22/01/2018	12/03/2018	Sangu	IWM
2	Anowara	21/01/2018	22/02/2018	Sangu	IWM
3	Bandarban	14/01/2018	14/02/2018	Sangu	IWM
4	Dohazari	Apr-1996	Sep 2016	Sangu	BWDB
5	Bandarban	Apr-1996	Sep 2016	Sangu	BWDB
6	Banigram	Apr-1996	Sep 2016	Sangu	BWDB

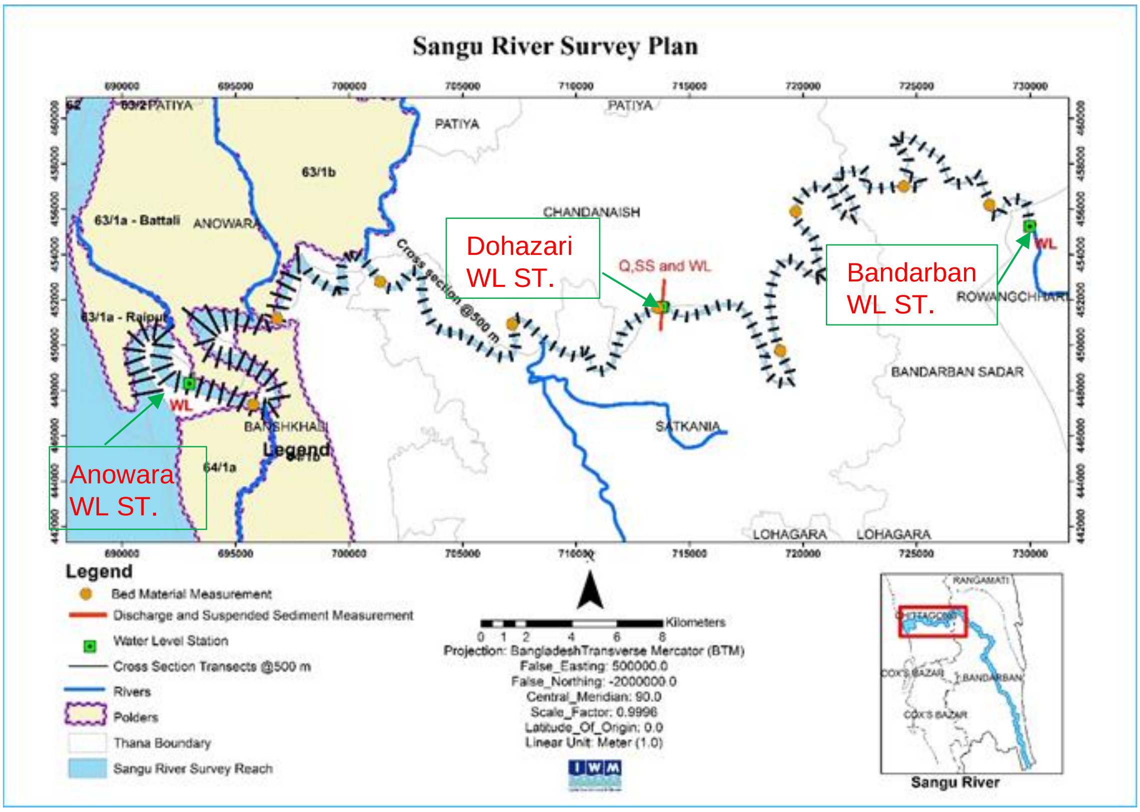

Figure 2-7 WL, Q, SSC & bed materials sample collection locations with cross sections in January 2018.

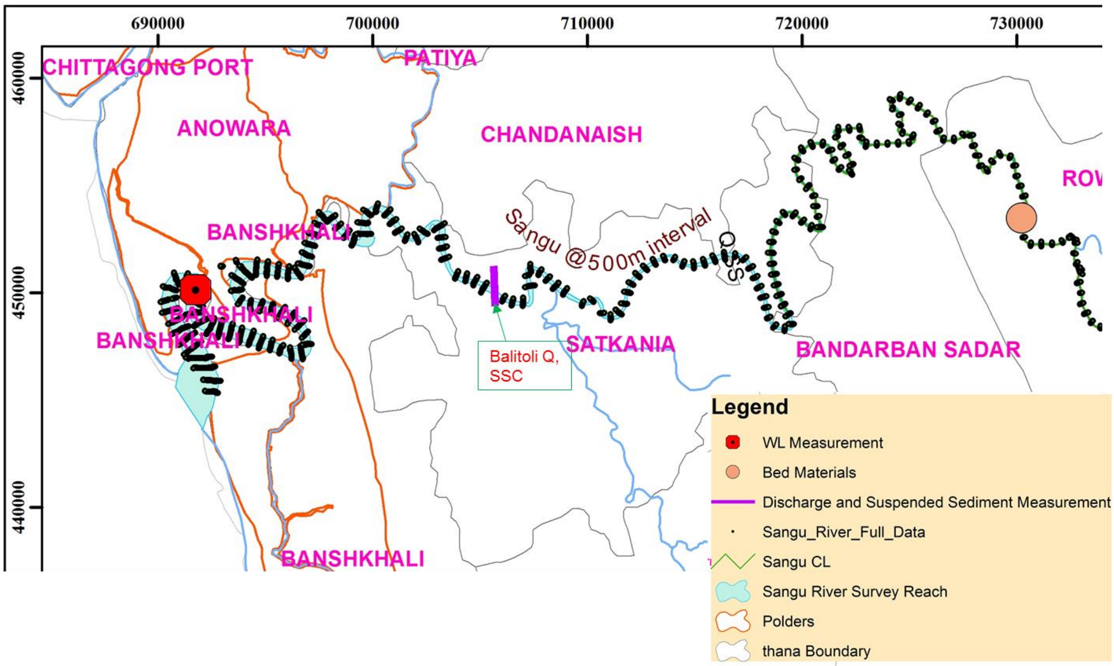

Figure 2-8 WL, Q, SSC & bed materials sample collection locations with cross sections in August 2020.

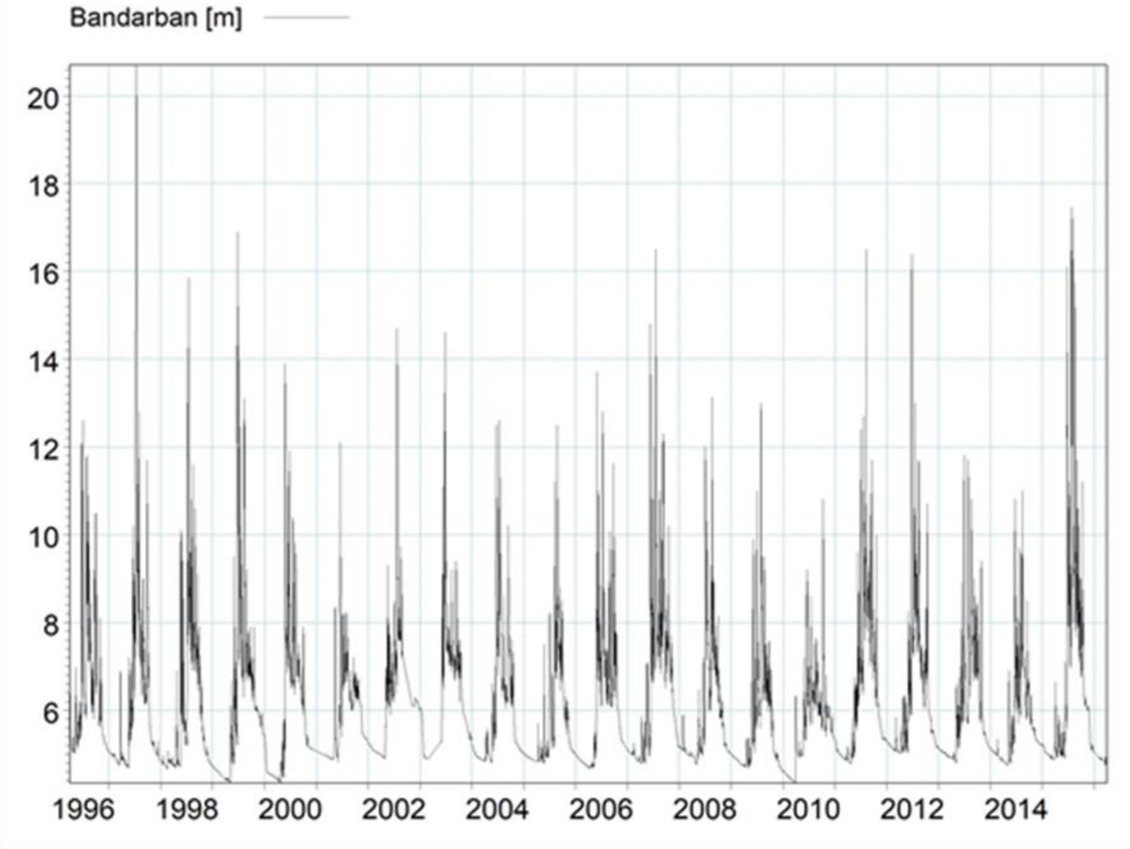

Figure 2-9 Time-series (1996 to 2015) water level @ Bandarban water level station (BWDB).

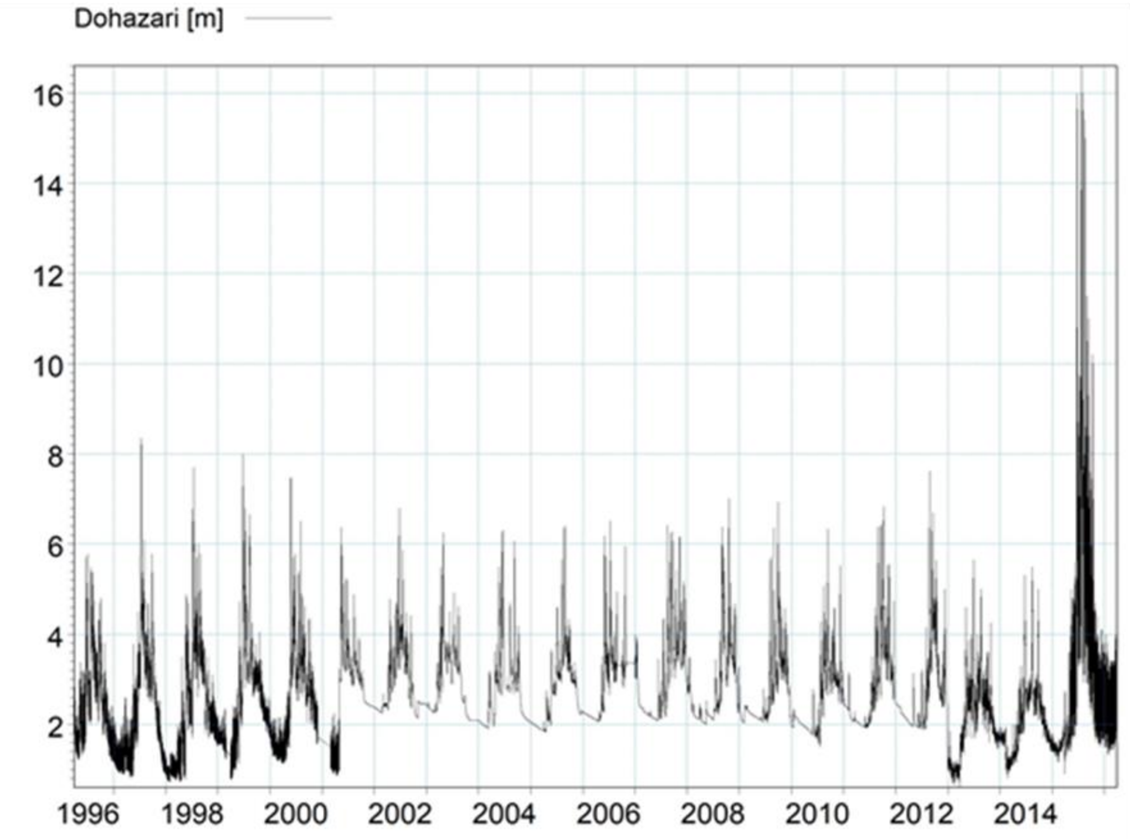

Figure 2-10 Time-series (1996 to 2015) water level @ Dohazari water level station (BWDB).

Bandarban is situated in the upstream part of the Sangu River, in a hilly area where the river width is getting smaller. BWDB has water level stations at Bandarban where the data has been collected. Historical data plot from 1996 to 2015 is shown in Figure 2-9. The peak monsoon water level goes up as high as 18 mPWD.

Dohazari station is situated almost 50 km upstream of the outlet. The tide could not reach up to this level. The long-term historical data from 1996 to 2015 has been plotted in Figure 2-10. The data shows high water level is 8 mPWD. In 2015 there was a flood in this region, but the data authenticity is not clear.

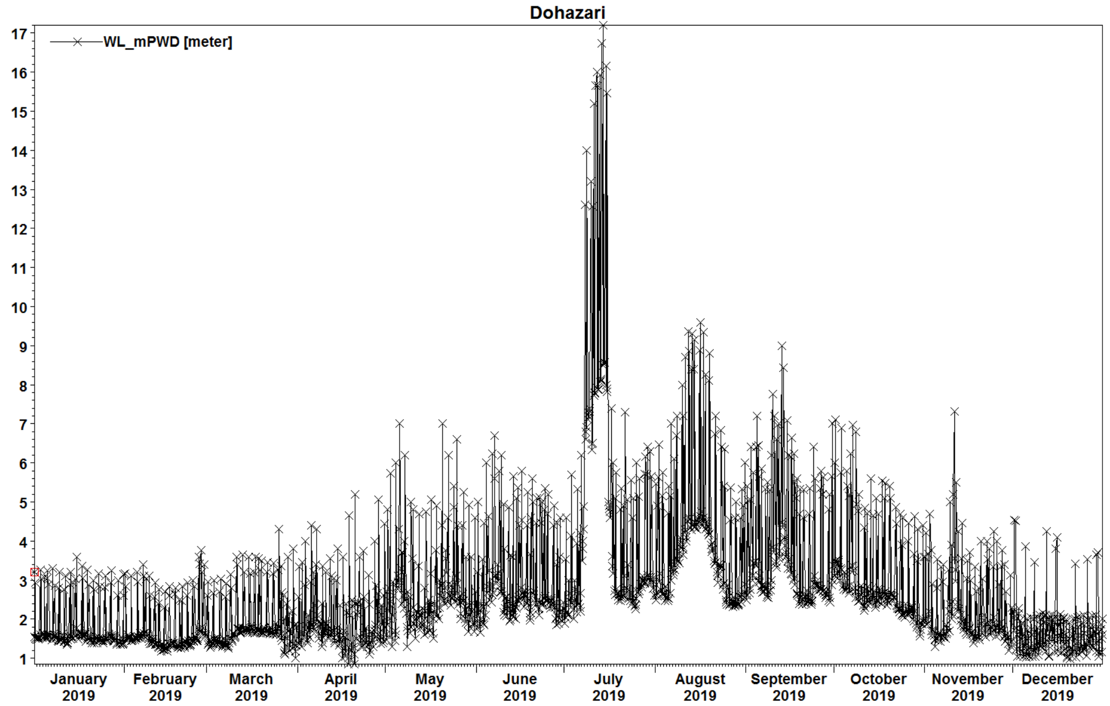

Figure 2-11 Time-series (2019) water level @ Dohazari water level station (BWDB).

Figure 2-11 shows the 2019 observed water level data from Dohazari. The figure shows that the highest water level at the Dohazari station was 17 mPWD in 2019.

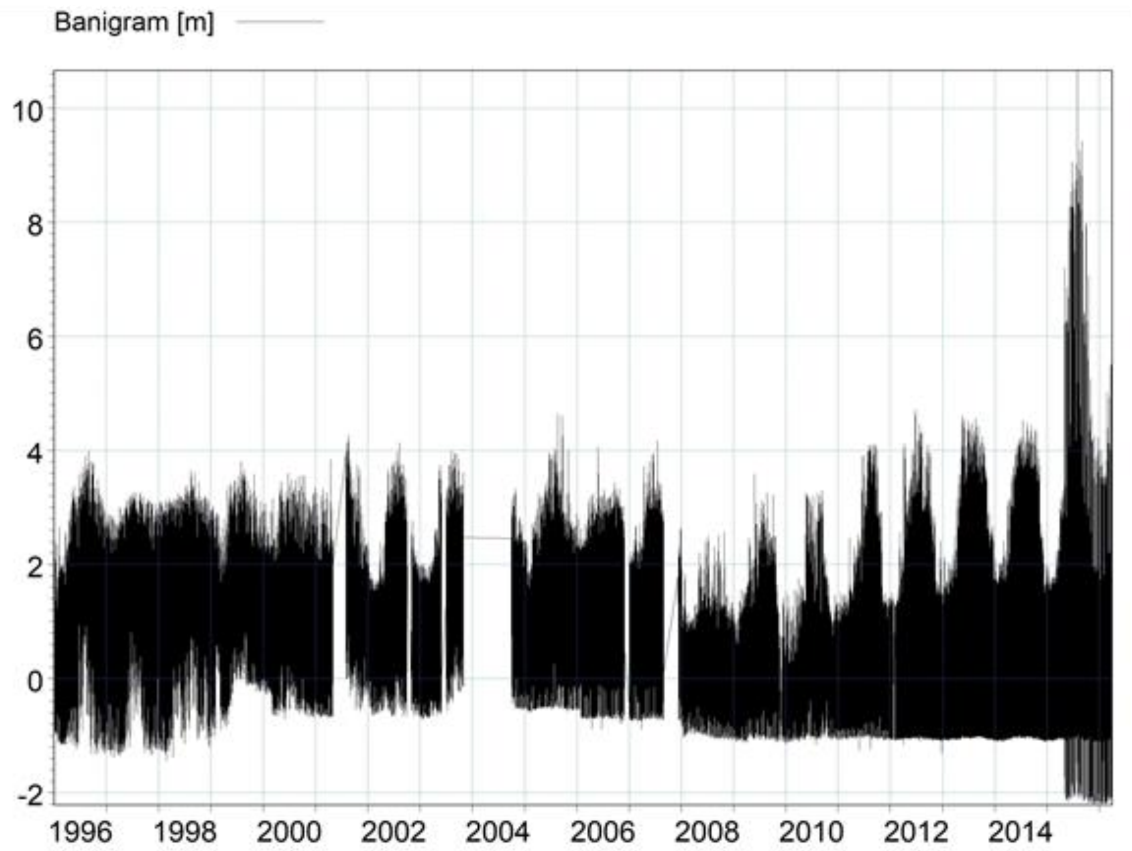

Figure 2-12 Time-series (1996 to 2015) water level @ Banigram water level station (BWDB).

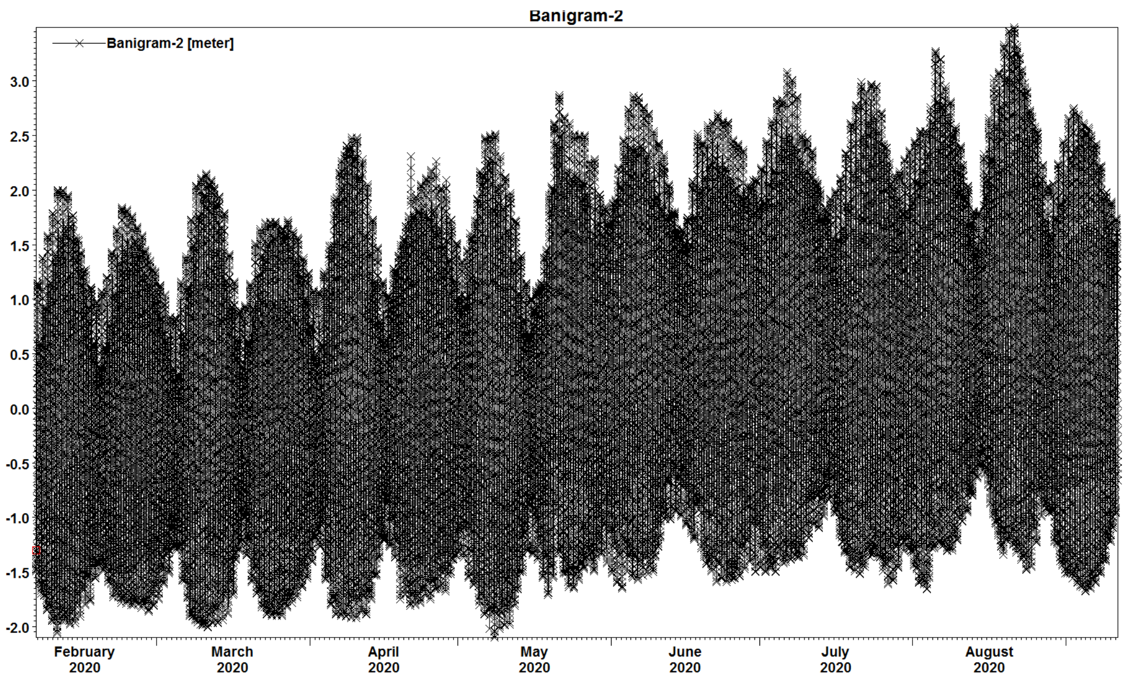

Figure 2-13 Banigram water level measured 2020 (IWM).

Banigram station is located close to the downstream boundary where the BWDB has a station. Historical data is available from this station, but for some years data is missing. In Figure 2-12 the historical data has been plotted, and the measured data in 2020 has been plotted in Figure 2-13.

2.3 Discharges time-series

Discharge is measured at Bandarban Dohazari and Balitoli in Sangu River. In Table 2-3 the discharge data and station have been named. The discharge measurements at Dohazari and Balitoli are plotted in Figure 2-14 to Figure 2-19. In dry periods the discharge is very low, but in monsoon the discharge suddenly goes up. In the below figures the scenarios have been explored.

Table 2-3 Discharge data for Sangu River.

Sl.	Date	Location	Easting	Northing	Source	River	Remarks	
	26/2/2020 & 5/3/2022	Balitoli	705466	450207	IWM	Sangu	Tidal	
1	07/02/2018	Dohazari	697019	452613	IWM	Sangu	Tidal	Spring
2	27/01/2018	Dohazari	697019	452613	IWM	Sangu	Tidal	Neap
3	Jan 2012 to Sep 2016	Bandarban			BWDB	Sangu	Non-tidal	Fortnightly measure-ment

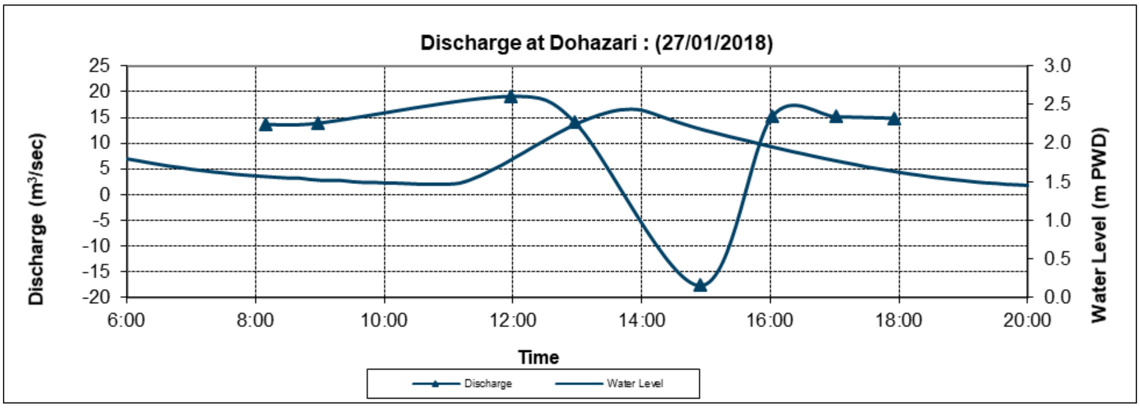

Figure 2-14 Measured discharge and water level @ Dohazari on 27/01/2018.

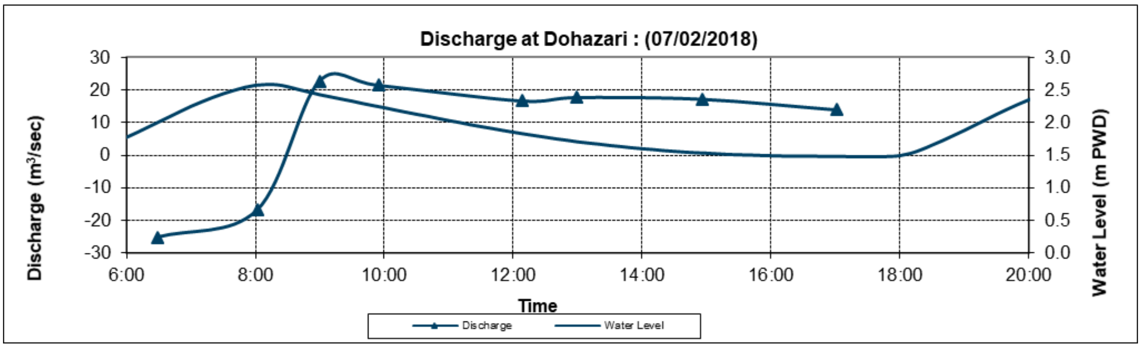

Figure 2-15 Measured discharge and water level @ Dohazari on 07/02/2018.

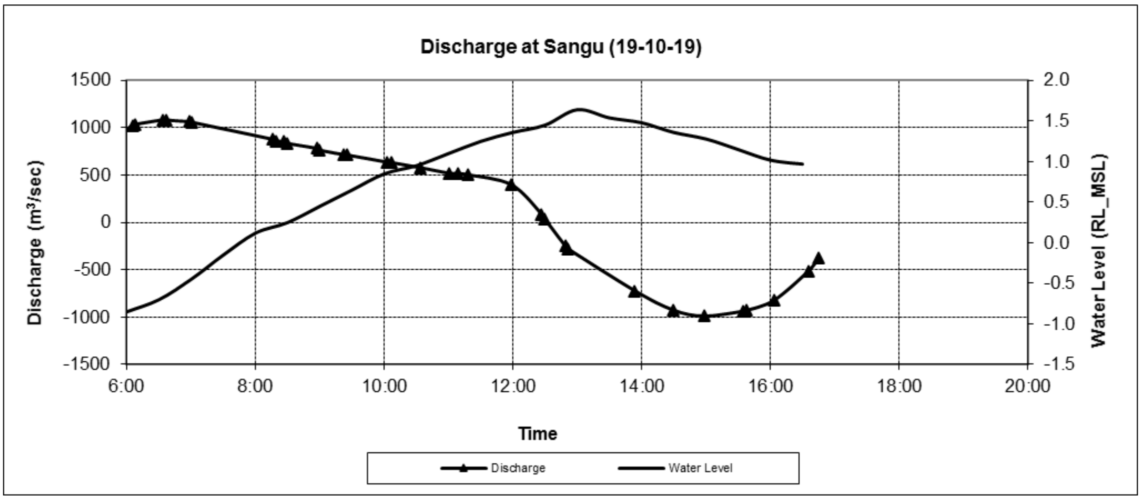

Figure 2-16 Measured discharge and water level @ Dohazari on 19/10/2019.

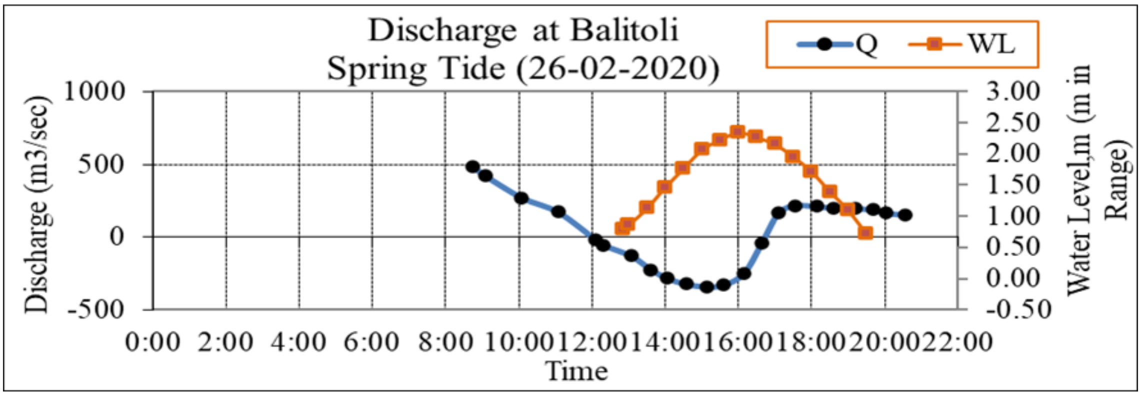

Figure 2-17 Measured discharge and water level on 26/02/2020 at Balitoli

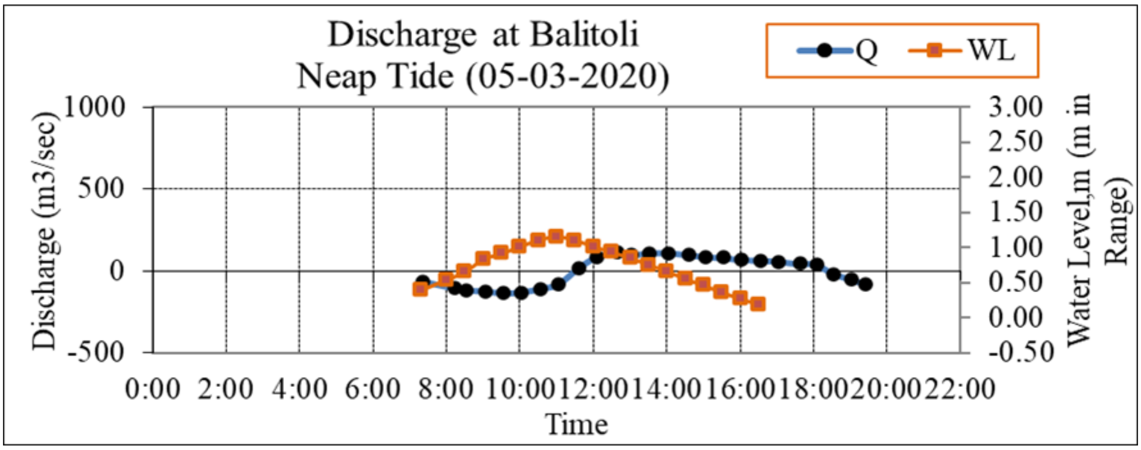

Figure 2-18 Measured discharge and water level on 05/03/2020 at Balitoli.

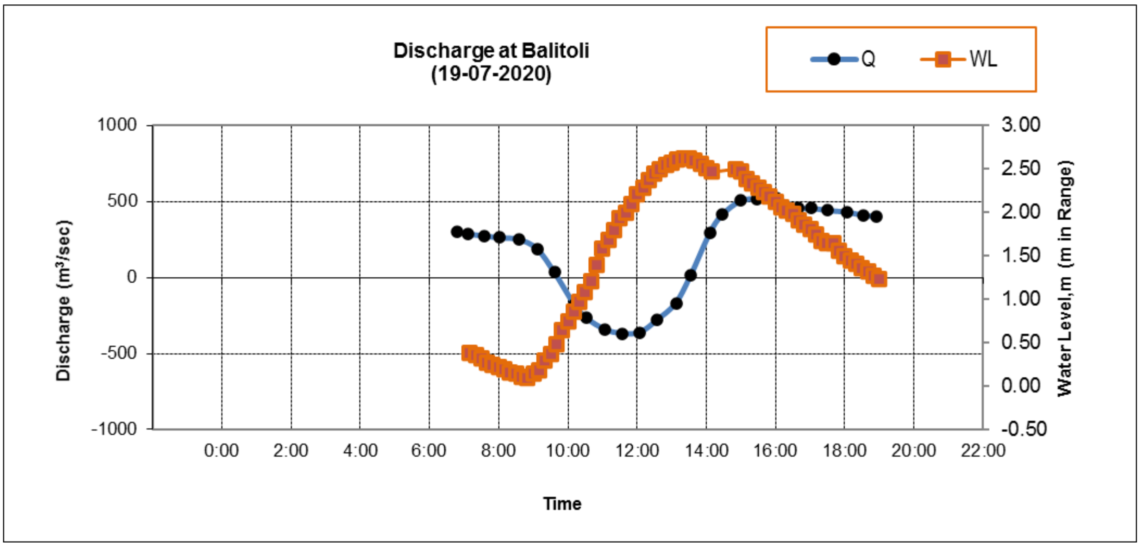

Figure 2-19 Measured discharge and water level on 19/07/2020 at Balitoli.

The discharge hydrographs plotted in the below Figure 2-20 and Figure 2-21 show that, in dry season the water flow is very low and in monsoon the scenario is completely different. In 2015, the maximum discharge comes as high as 1800 m³/s in Bandarban.

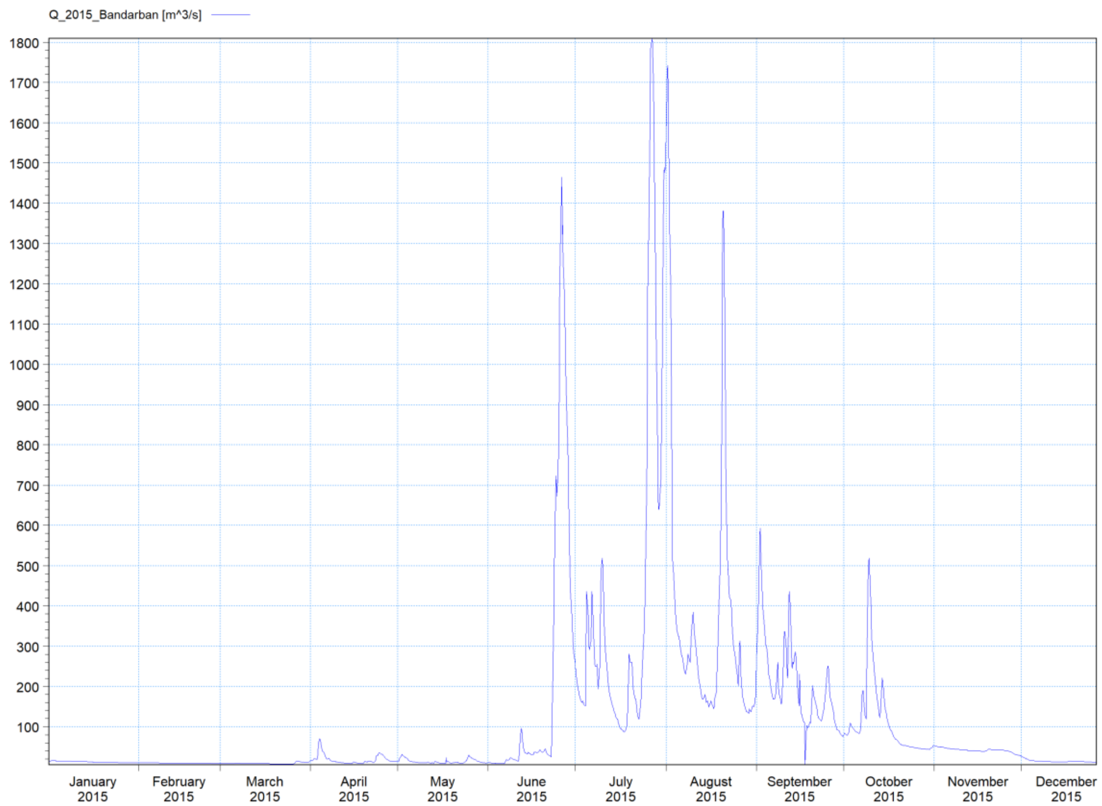

Figure 2-20 Time-series discharge at Bandarban from January 2015 to December 2015.

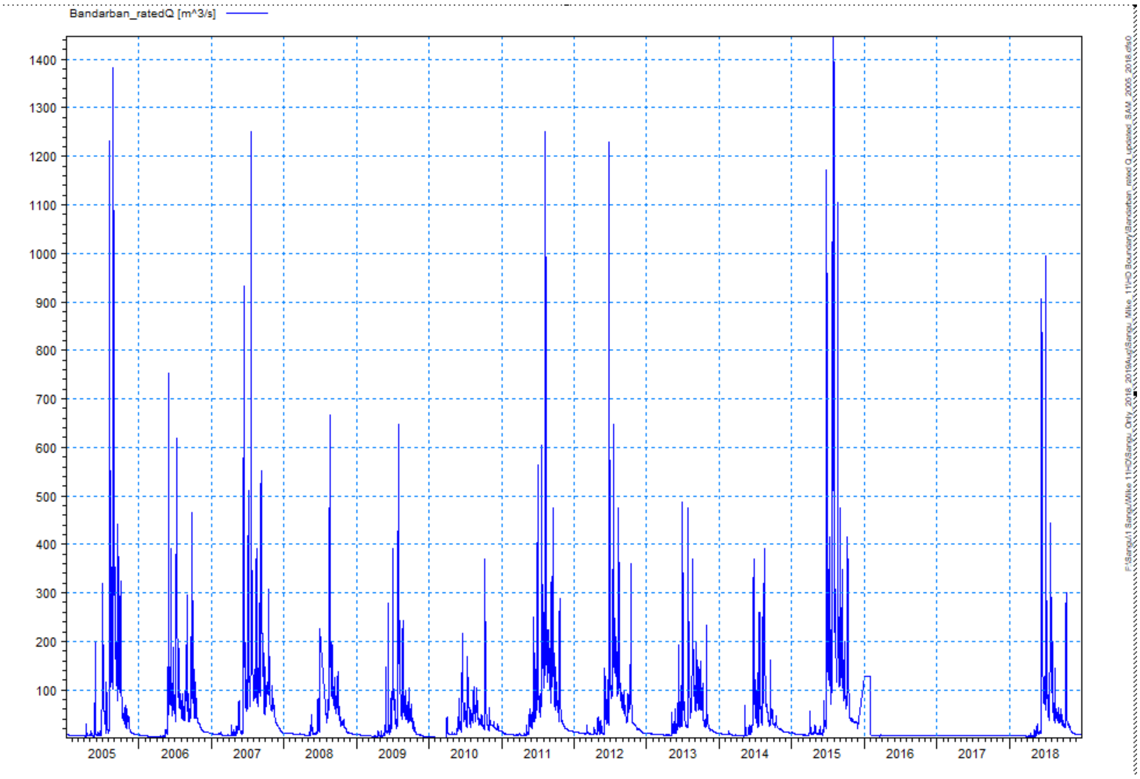

Figure 2-21 Time-series discharge at Bandarban from January 2005 to December 2018 (2016 & 2017 missing).

2.4 Sediment bed samples

The samples are collected from the main river channel and both banks across the same cross-section. The value of median diameter of the collected bed sample, i.e. d_{50}, is calculated for each sample. The bank materials are dominated by sand with some gravel (particle size varies from 0.063 to 4mm). Riverbed materials collected from Sangu River reveal that sand is predominant in the riverbed. Average particle size (d_{50}) of sediment varies from 0.17 mm to 0.34 mm in most locations of the Sangu riverbed.

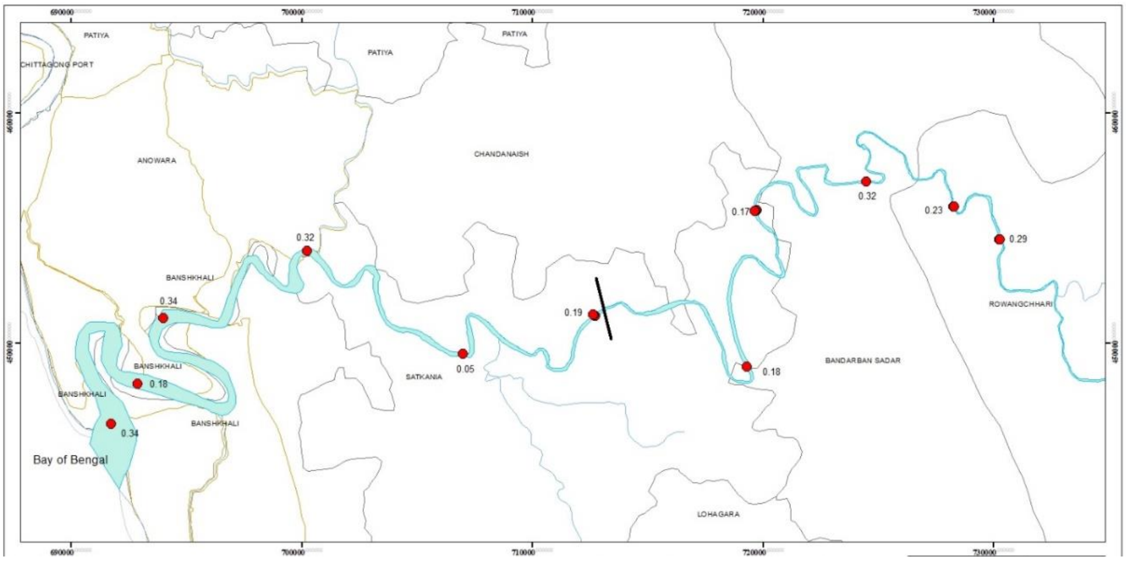

Figure 2-22 Bed sample locations, 2018.

Table 2-4 Bed samples for Sangu River.

SL	River Name	Station Name	Date	Easting	Northing	D_{50} (mm)
1	Sangu	X_03_CL	11-02-18	691702	446498	0.339
2	Sangu	X_20_CL	11-02-18	692856	448213	0.179
3	Sangu	X_40_CL	11-02-18	693965	451083	0.336
4	Sangu	X_60_CL	22-01-18	700212	454000	0.317
5	Sangu	X_80_CL	22-01-18	706967	449522	0.048
6	Sangu	X_100_LB	22-01-18	712707	451160	0.314
7	Sangu	X_100_CL	22-01-18	712660	451203	0.189
8	Sangu	X_100_RB	22-01-18	712642	451232	0.31
9	Sangu	X_120_CL	20-01-18	719312	448974	0.177
10	Sangu	X_140_LB	20-01-18	719721	455751	0.185
11	Sangu	X_140_CL	20-01-18	719678	455742	0.173
12	Sangu	X_140_RB	20-01-18	719640	455729	0.149
13	Sangu	X_160_CL	20-01-18	724471	456996	0.319
14	Sangu	X_180_LB	20-01-18	728269	455920	0.174
15	Sangu	X_180_CL	20-01-18	728289	455923	0.225
16	Sangu	X_180_RB	20-01-18	728310	455915	0.267
17	Sangu	X_188_LB	20-01-18	730259	454492	0.241
18	Sangu	X_188_CL	20-01-18	730298	454500	0.294

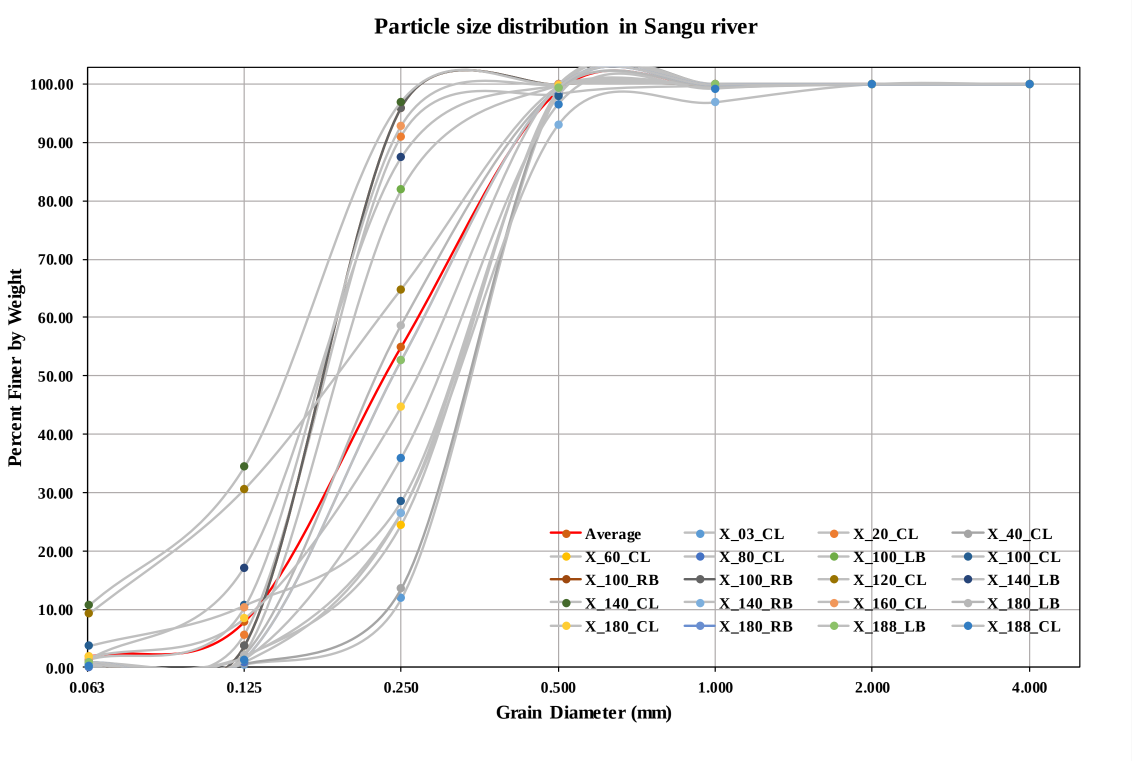

Figure 2-23 Particle size distribution of bed sediment in the Sangu River systems. IWM data, 2018.

The locations are indicated in Figure 2-22, while the particle size distributions are shown in Figure 2-23. The bed samples were used for establishing the sediment model sediment sizes and fractions. From the particle distribution it is found that the sediment is sandy.

2.5 Suspended sediment data

The available SSC observations are shown in Table 2-5. It is noted that these are all from the dry season, while the river is highly seasonal with very low flows in the dry season and high flows in the monsoon. Monsoon SSC data would be more valuable.

Table 2-5 Suspended sediment data for Sangu River.

SL	Location	Source	River	Date
1	Dohazari	IWM	Sangu	27/01/2018
2	Dohazari	IWM	Sangu	07/02/2018

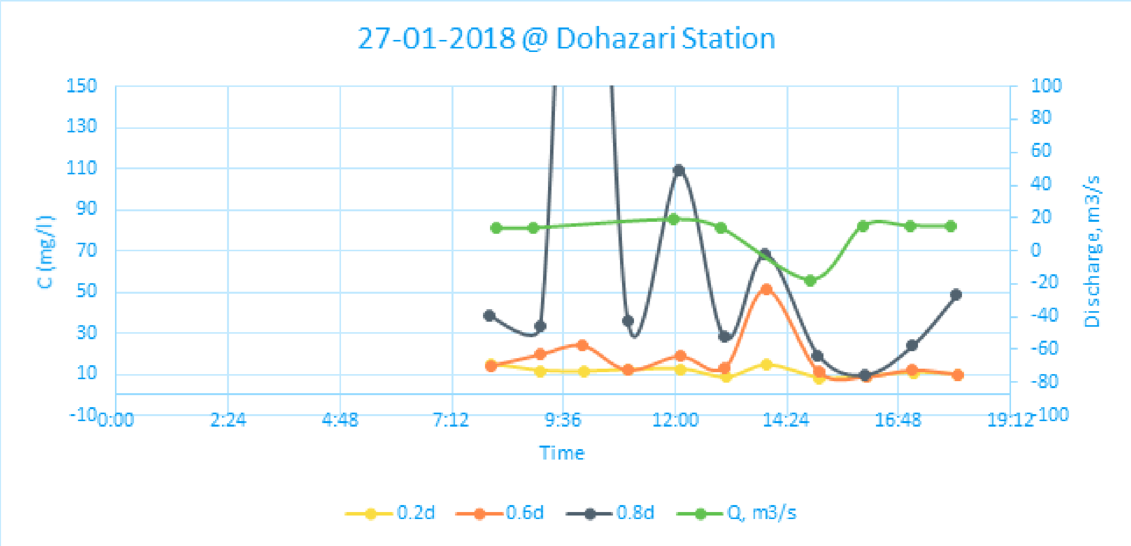

Figure 2-24 Suspended sediment concentration and discharge plot on 27/01/2018 at Dohazari.

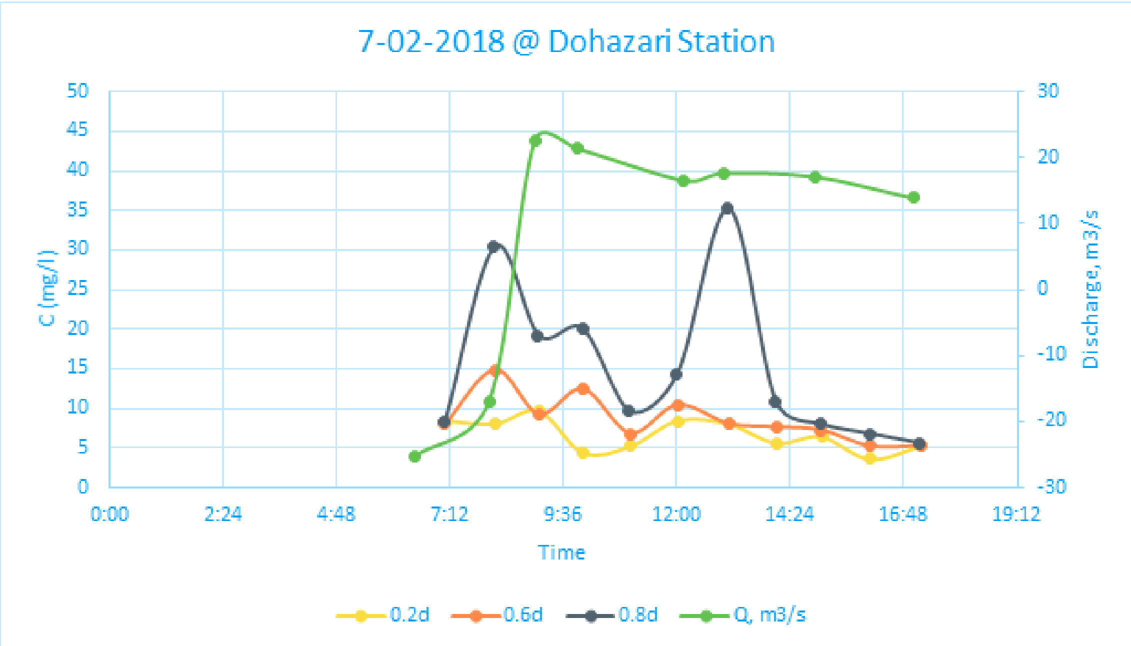

Figure 2-25 Suspended sediment concentration and discharge plot on 07/02/2018 at Dohazari.

2.6 Suspended sediment particle size distribution data

Suspended sediment particle size distribution data is not available for the Sangu River. However, such data is less important for a sandy river compared to a river dominated by silt. Hence, the lack of such data is not a serious issue for the Sangu River.

2.7 Historical bank lines from satellite imagery

In the study area, nine cloud-free scenes of Landsat imagery were acquired for the period of 1988–2019 from the Earth Explorer database of the U.S. Geological Survey. The time of acquisition of the images was mainly during the dry season from November to February as there were no clear images during other seasons. All the extracted riverbank lines are presented in Figure 2-28 for the Sangu River system up to Dohazari bridge. Sentinel image has been collected from 2016 to 2020.

For the inspection of erosion, Landsat imagery were acquired for the period of 1988-2019. IWM engineers digitized the bank lines 1988 to 2019, typically every 5 years, to have the data available for the model study. Figure 2-26 presents all the extracted bank line for the Sangu River.

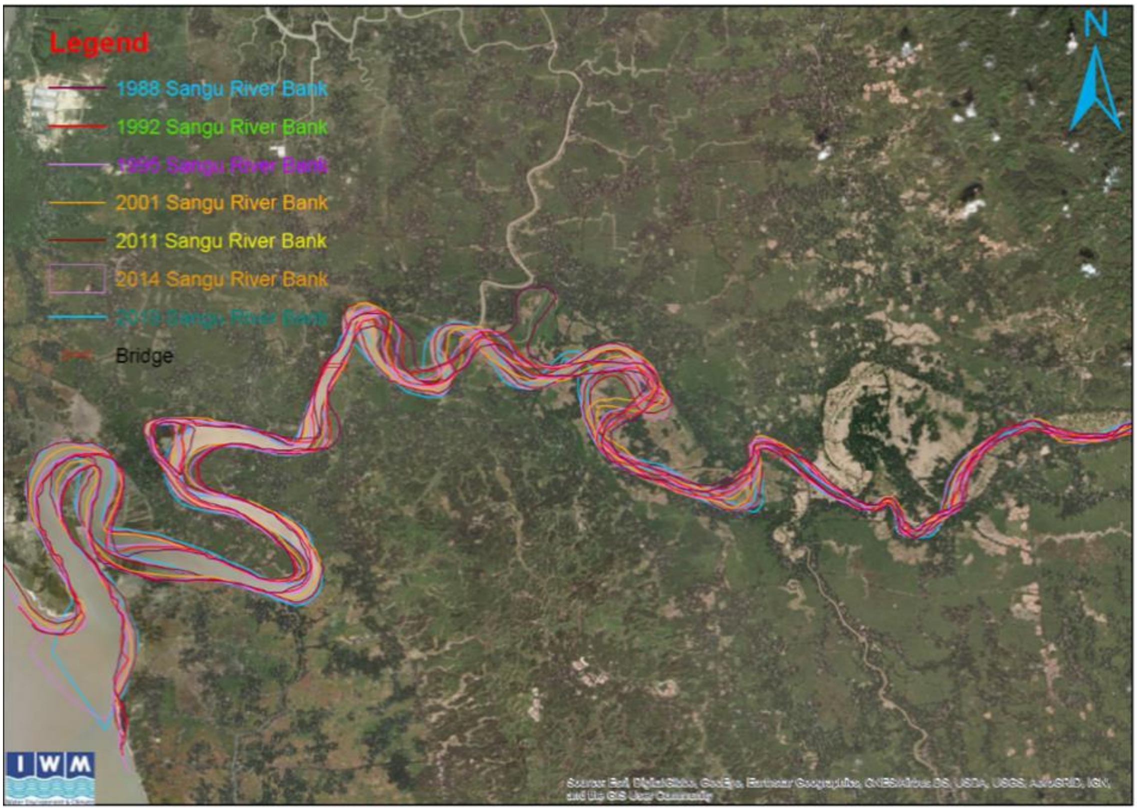

Figure 2-26 Bankline from year 1988 to 2019 of Sangu River up to Dohazari bridge.

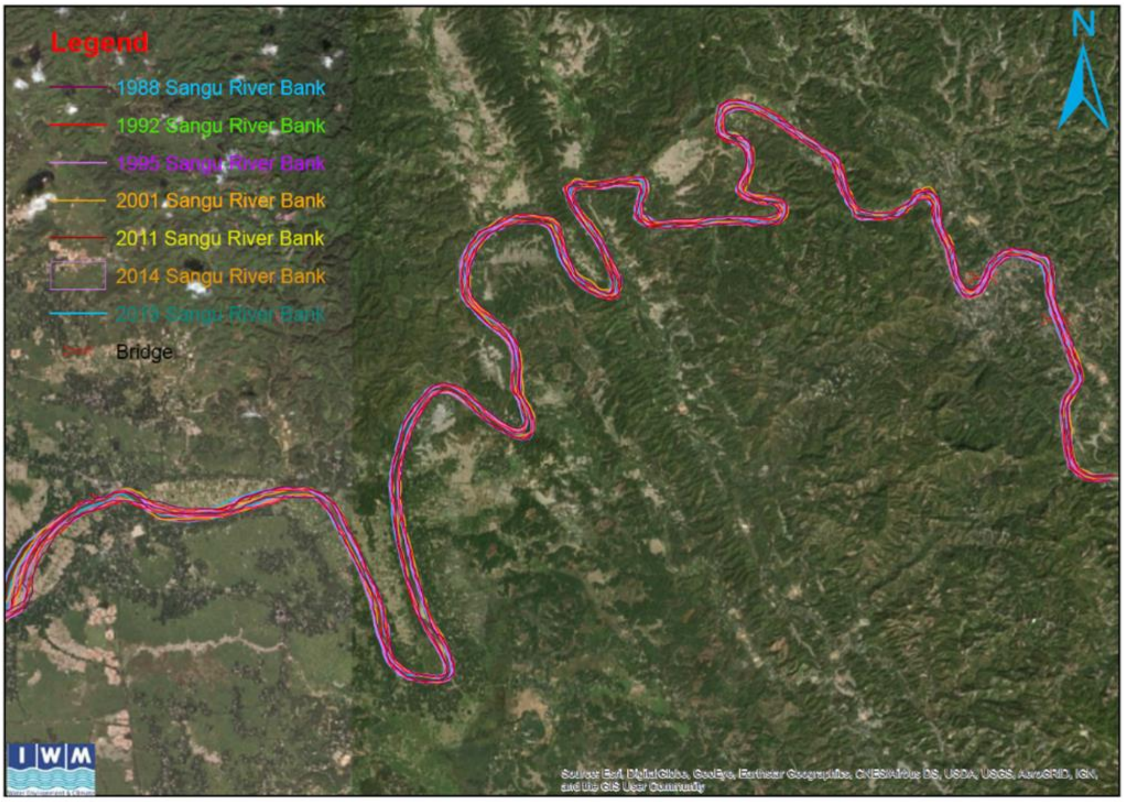

Figure 2-27 Bankline from year 1988 to 2019 of Sangu River from Dohazari bridge to Kalaghata road bridge.

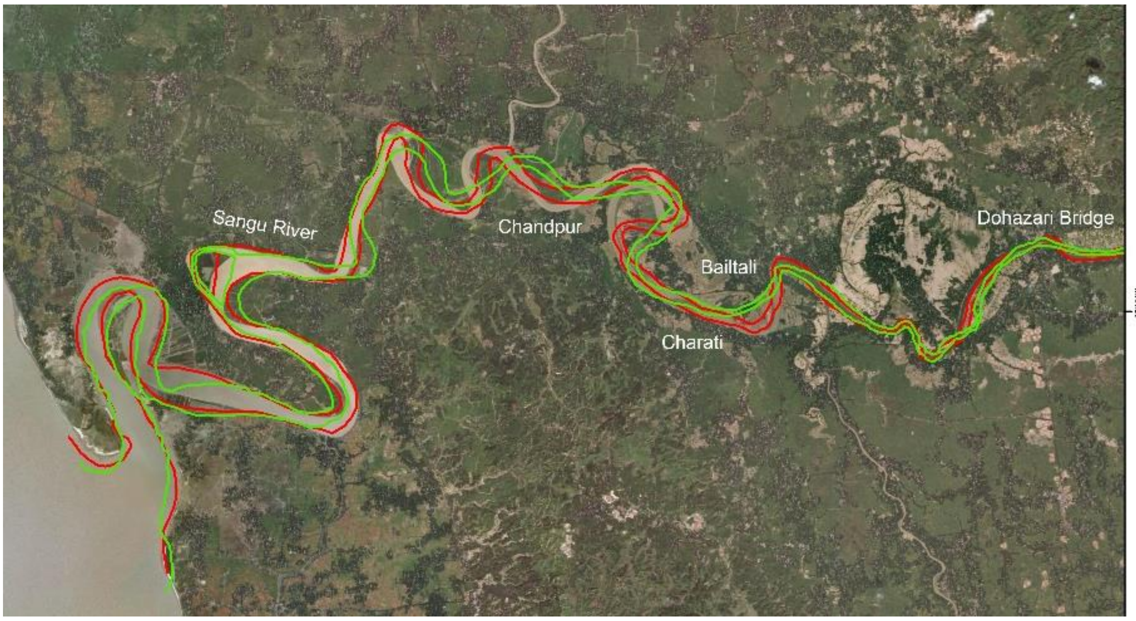

Figure 2-28 Bankline from year 1988 to 2001 of Sangu River from outfall to Dohazari bridge.

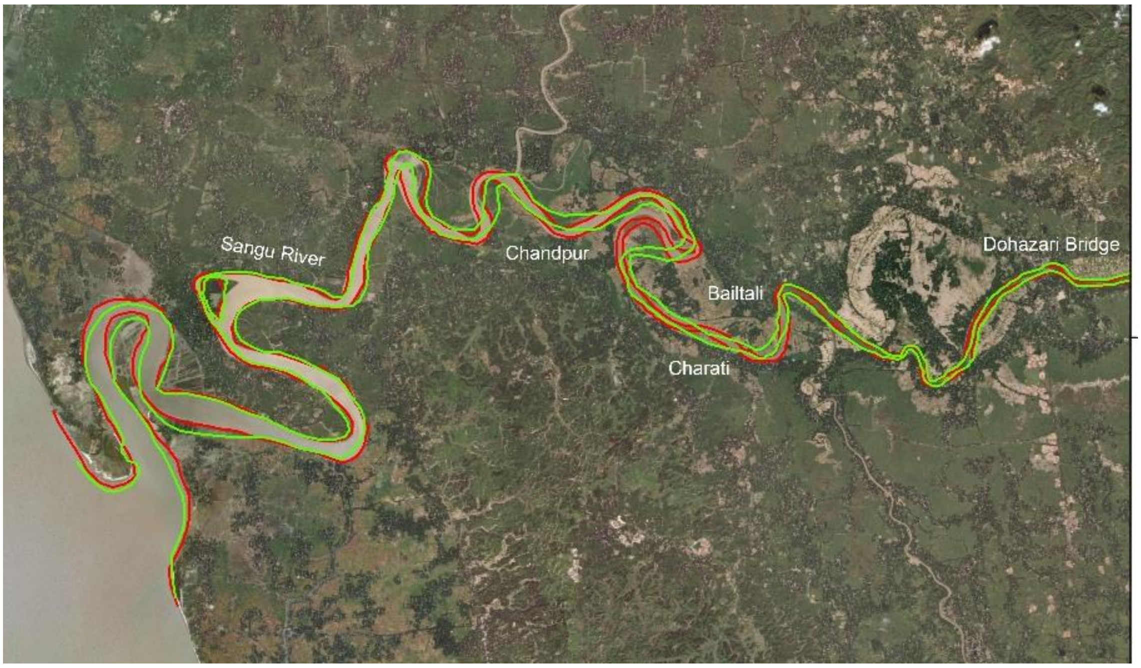

Figure 2-29 Bankline from year 2001 to 2011 of Sangu River from outfall to Dohazari bridge.

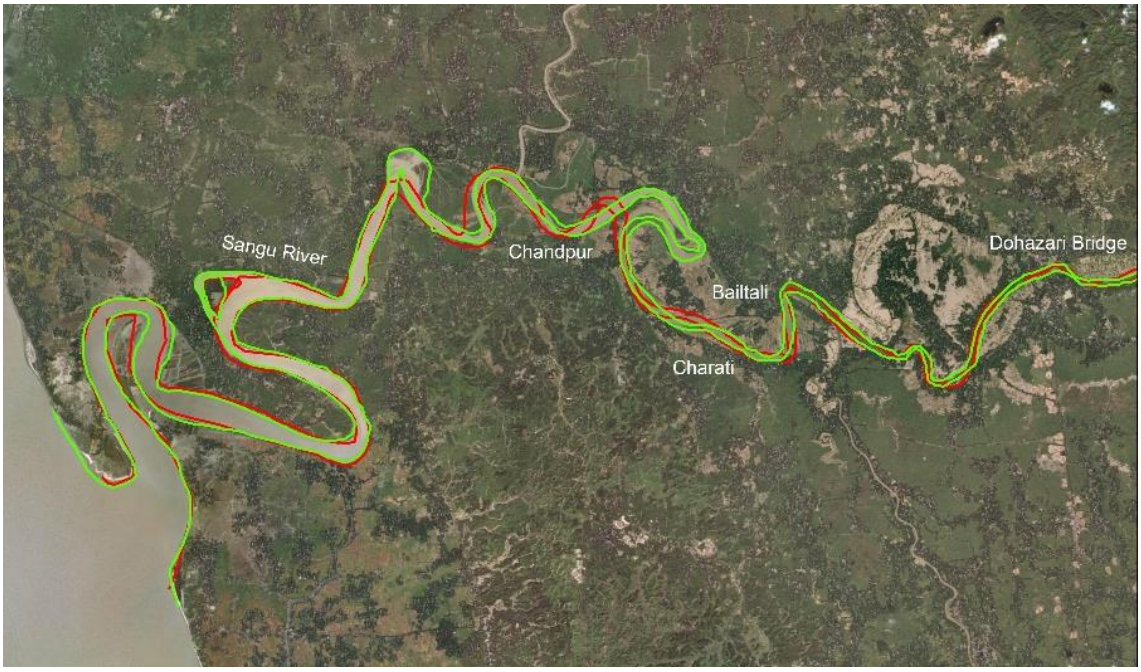

Figure 2-30 Bankline from year 2011 to 2019 of Sangu River from outfall to Dohazari bridge.

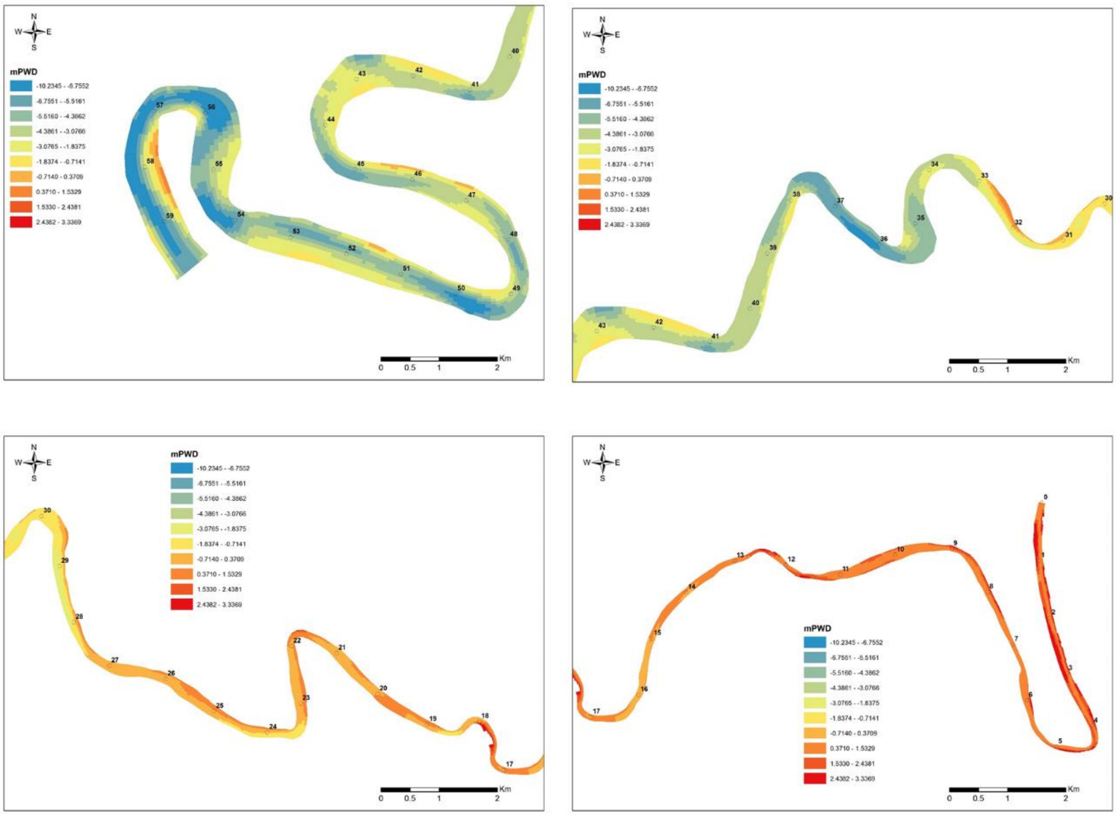

Figure 2-31 Chainages along Sangu River.

The Sangu River is flashy and high-water flow and current velocities during the monsoon cause riverbank erosion. Downstream reaches of the river are meandering, and helical flow in the meandering bank causes erosion of the outer bank.

Erosion-vulnerable areas have been identified, and it has been found that all the meandering bends (outer bends) in Sangu River, from its outfall to Dohazari bridge, are facing erosion. BWDB has made bank protection works at different places. Some eroding banks in the downstream of Sangu River and BWDB bank protection works are presented in Figure 2-32.

BWDB is continuously working on the bend erosion, and some pictures are shown below.

Erosion near Sangu Outfall, Anwara

Bank erosion near Banigram

Erosion near Sangu Outfall, Anwara

Bank erosion near Banigram

Figure 2-32 Observed bank erosion 2018 along Sangu River during field visit.

The bank lines were processed into erosion as a function of chainage, which is useful for model calibration. However, for the Sangu case we have conducted hindcast simulation, e.g. 2018-2020, because we only have a 2018 and a 2020 bathymetry. The bank erosion 2018-2020 was therefore processed into erosion as a function of the 2018 grid coordinates.

The observed bank erosion along both the banks as a function of chainage are shown in Figure 2-33 and Figure 2-34. For illustration of the strong correlation with bed levels, we also added 2020 bed levels.

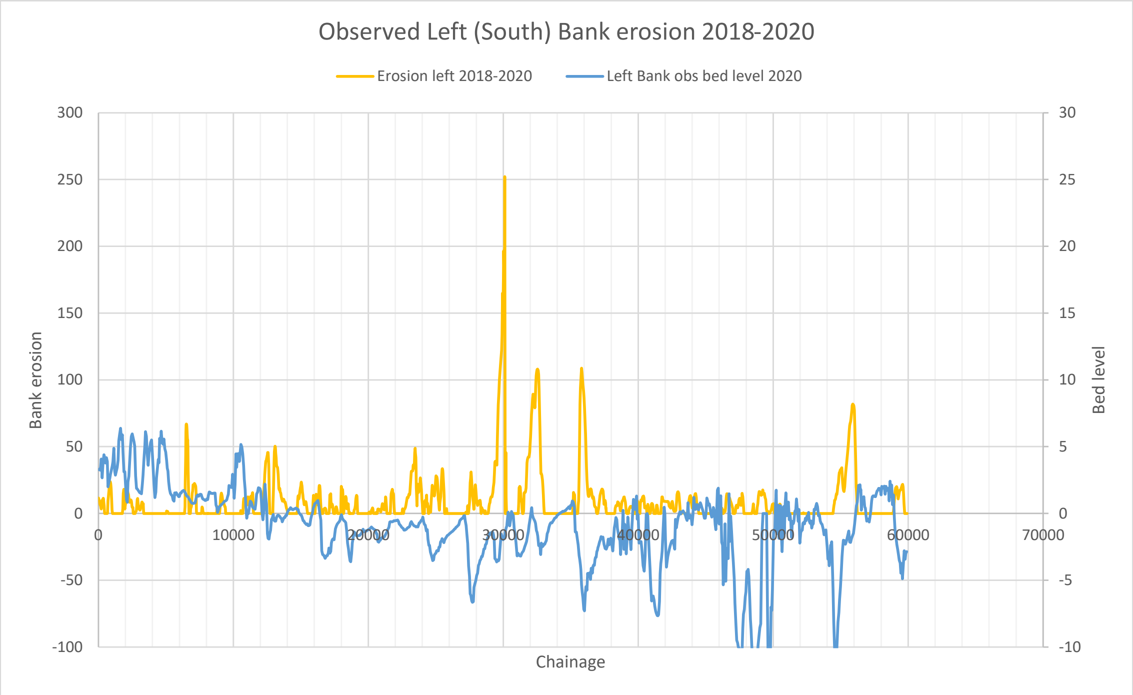

Figure 2-33 Observed left bank erosion 2018-2020 along Sangu River as a function of chainage with bed level of 2020.

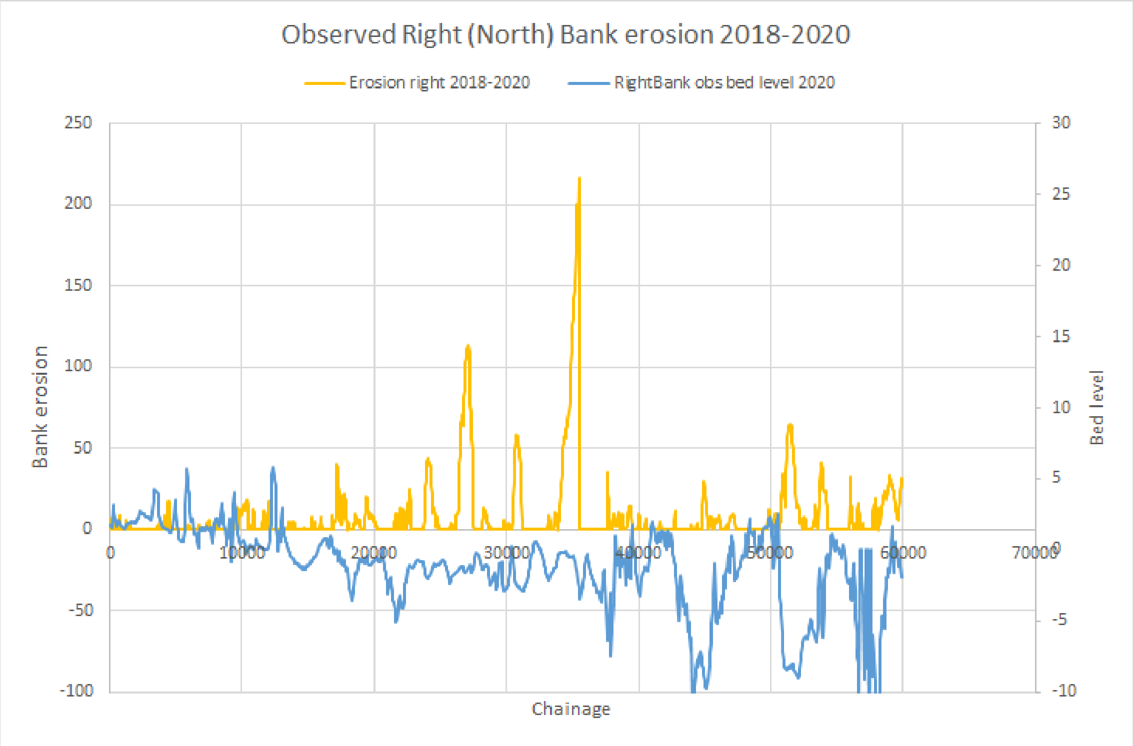

Figure 2-34 Observed right bank erosion 2018-2020 along Sangu River as a function of chainage with bed level of 2020.

2.8 Existing Bank protection works

A lot of bank protection works have been found in both banks of the Sangu River. In Figure 2-35 the existing bank protection works are shown.

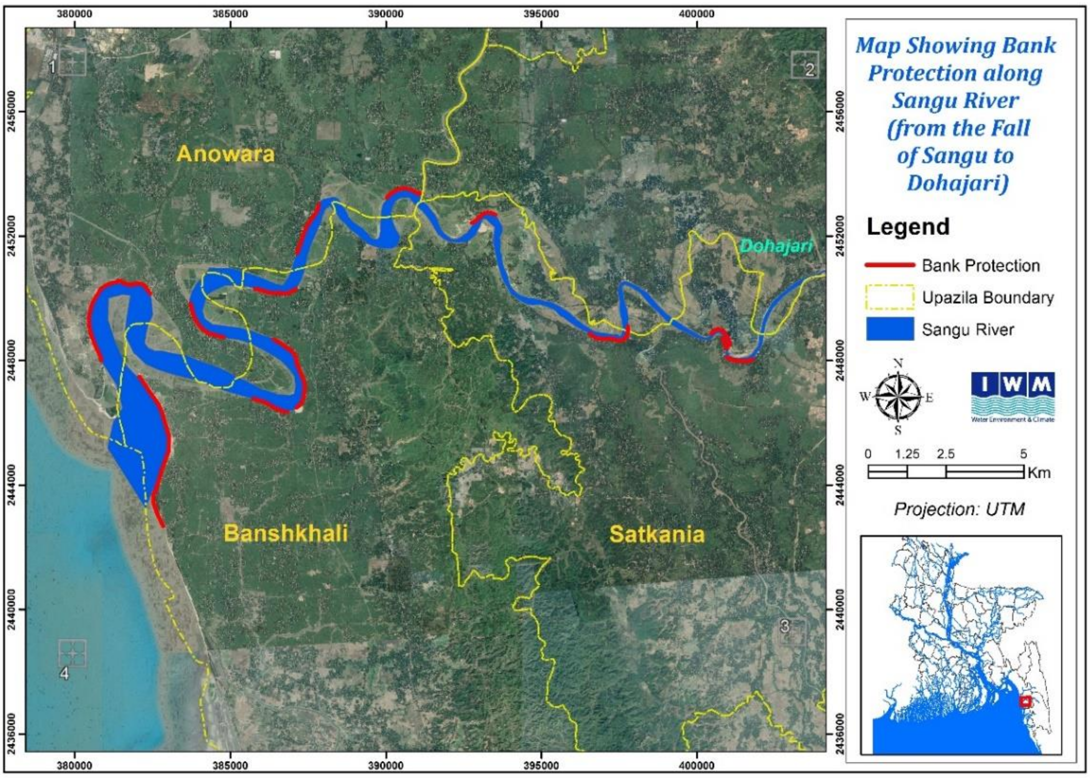

Figure 2-35 Bank protection works of Sangu River from outfall to Dohazari bridge.

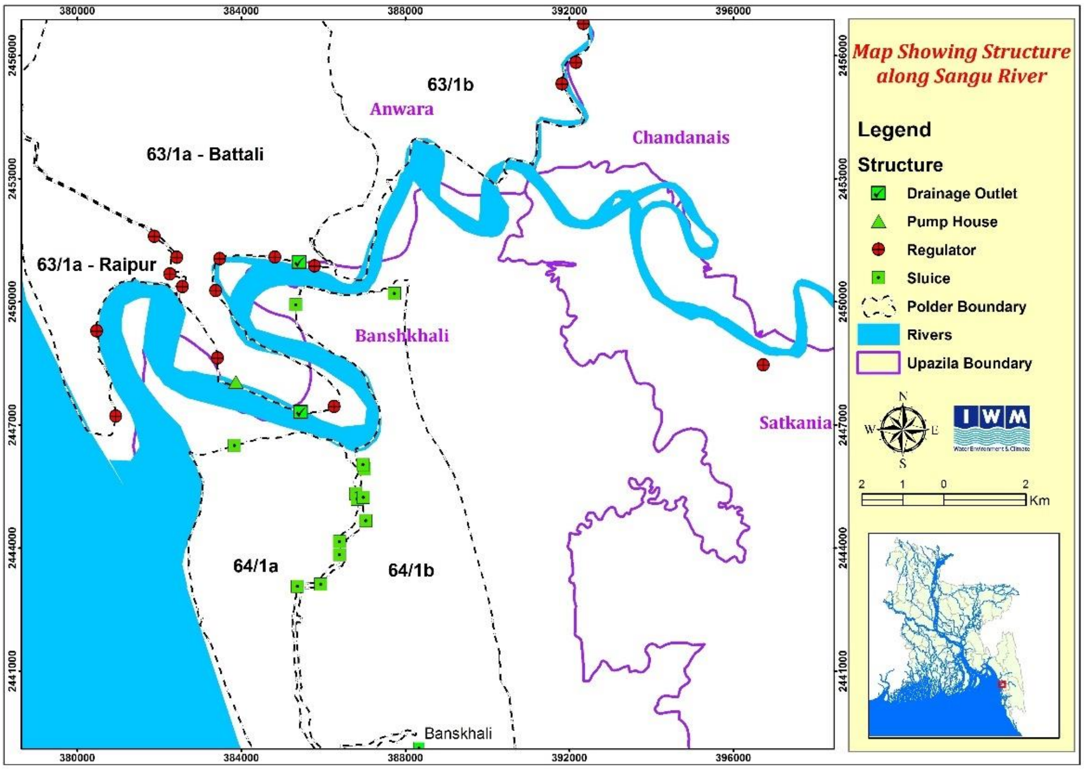

Figure 2-36 Existing structures of Sangu River from outfall to near Dohazari bridge.

There are four polders (BWDB projects) along the Sangu River (polder 63/1A, 63/1B, 64/1A, 64/1B). The polders have flood embankments with drainage structures. In the Figure 2-36 the flood embankment outline and structure locations are shown.

	
Bank protection work, Premashia Bazar, Sangu River	Erosion near Sangu outfall, Anowara
	
Bank protection work, Premashia Bazar, Sangu River	Erosion at west Amilaish

Figure 2-37 Bank protection works pictures of Sangu River near outfall left bank.

As seen in the Figure 2-37, Premashia bazar has a bank protection work near the outfall. Just above the bank protection work there are some natural protections, i.e. mangrove trees are seen. For Anowara and Amilaish there is erosion in the downstream bends.

3 Model development

The model extent was selected based on the following criteria:

- Include all erosion along polders
- The upstream boundary should not be tidal
- The upstream boundary should be in a straight reach

This resulted in a model that does not include all the bathymetry data.

3.1 Grid and bathymetry

Under the present study, a dedicated model has been developed for Sangu River. With the curvilinear grid, it is expected that the flow interaction would be more representative of field condition. The model simulates hydrodynamic and morphological parameters in every computational grid point. The computational grids were generated using the measured bank lines of monsoon 2018 based on the following criteria:

- The grid should be aligned to the natural streamlines
- The grid line should follow the bank lines; and
- The grid must be orthogonal.

To simulate the morphological model with different hydrological events, the bathymetry data was superimposed on the curvilinear grid along with flow discharge and water level data in the upstream and downstream of the model, respectively. This means that every grid cell contains river cross-section data, and after model simulation every grid cell produces hydrodynamic and morphological parameters like water level, discharge, water depth, velocity, bed scour/deposition and others. For Sangu River we have 2018 and 2020 bathymetry data available, and the 2018 bathymetry has been used to develop the model as initial bathymetry. Figure 3-1 presents the computational grid.

Figure 3-1 shows the curvilinear grid used for the model development. The bathymetry of the model has been prepared based on data from the IWM bathymetric survey carried out during 2018. This bathymetry has been used as input (initial bed level) of the model, shown in Figure 3-2.

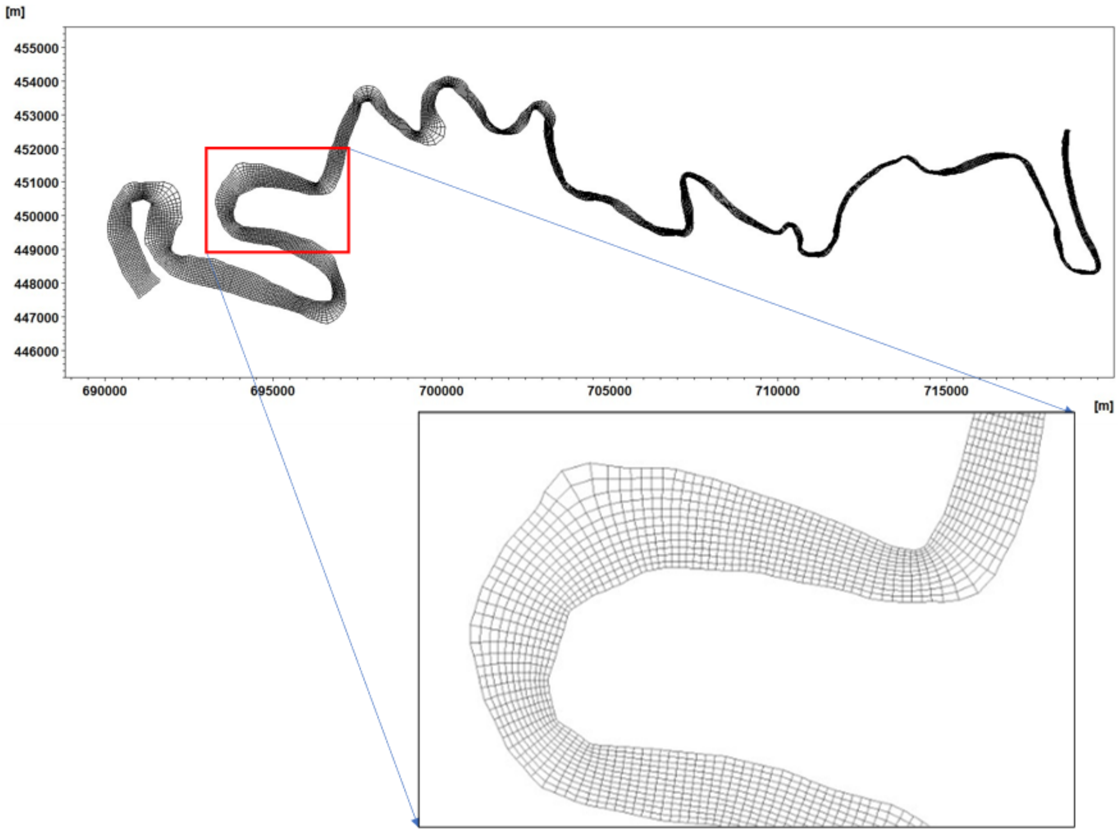

Figure 3-1 Computational grid for the Sangu model, 1000x13 grid points.

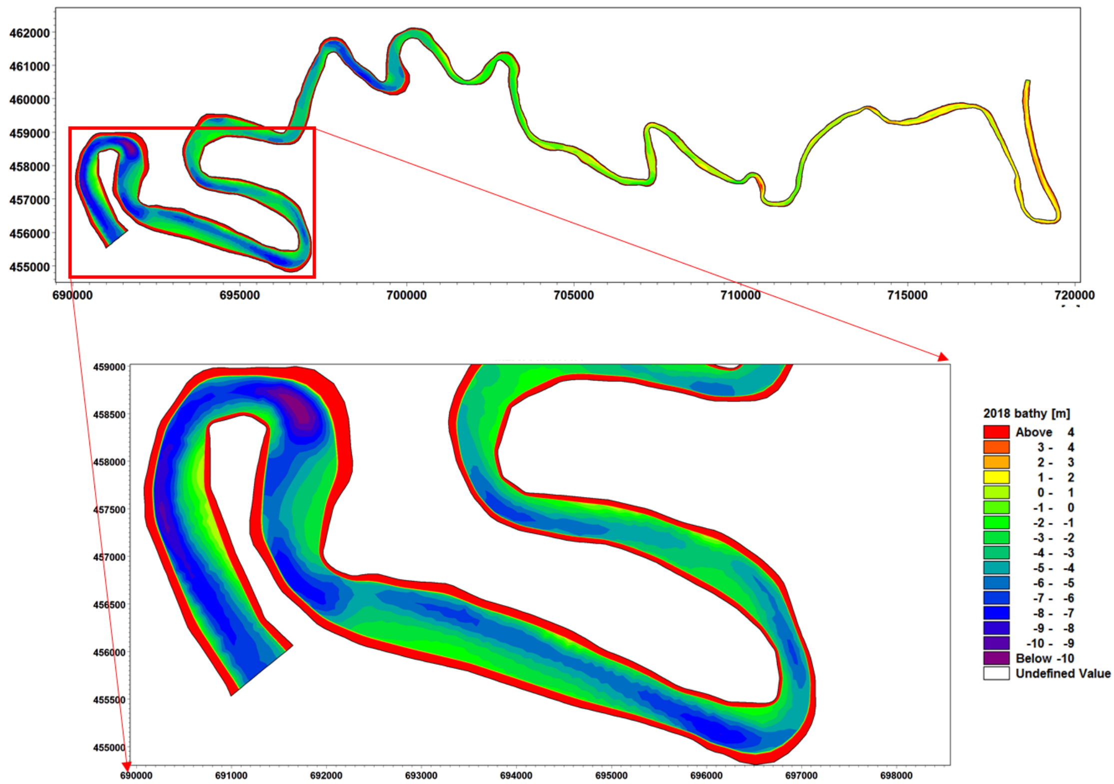

Figure 3-2 Contoured bathymetry of 2018.

3.2 Boundary conditions (hydrodynamic model)

The upstream boundary has been extracted from the calibrated one-dimensional Eastern Hilly Regional Model (EHRM). In the hydrodynamic model, the upstream boundary comes from the EHRM model as discharge, and downstream the water level data has been extracted from the updated (2018 & 2019) Bay of Bengal model.

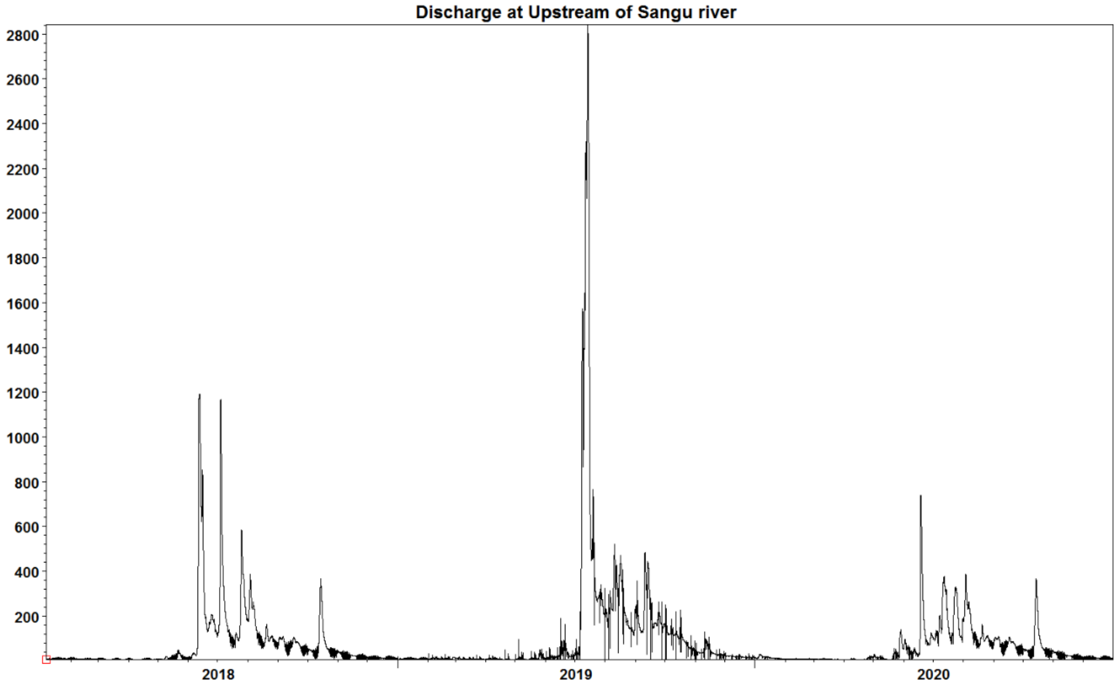

Figure 3-3 MIKE 21C upstream boundary (discharge 2018 to 2020) from one-dimensional model.

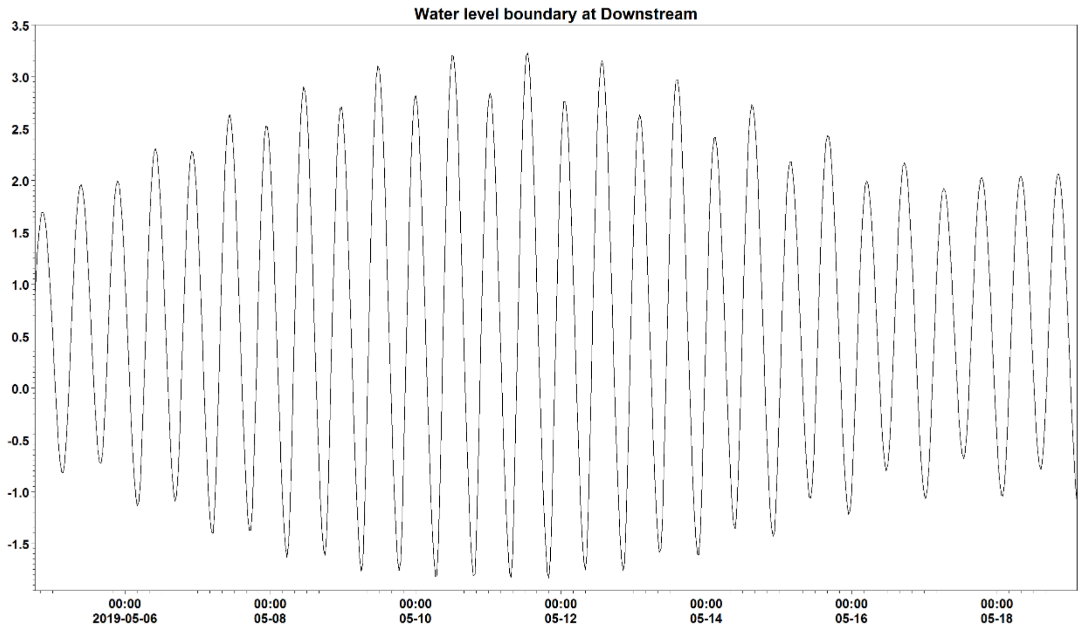

Figure 3-4 MIKE 21C downstream boundary (water level) from Bay of Bengal model.

From the calibrated Bay of Bengal model, we have also extracted the downstream water level boundary. There are no significant tributaries or distributaries along the Sangu River model. Hence the model only contains the upstream discharge and downstream water level boundary conditions.

3.3 Hydrodynamic calibration and validation

The calibrated and validated hydrodynamic model is needed to develop a reliable MIKE 21C bank erosion sediment transport model.

We have calibrated for 2018 and 2019, keeping in mind that the bathymetry is from 2018.

The resistance calibration was partly inherited from the MIKE 11 EHRM. The resistance coefficient used is Manning M=40 $m^{1/3}/s$.

It is noted that the morphological model was developed with the same resistance formulation, which still yielded good calibration. The resistance number in deep channels is most important in the calibration to discharges and water levels, while the shallow water resistance is morphologically important. Again, we note that there are no ADCP velocity profiles.

The model was calibrated with field data from the dry season in 2018 and the 2019 monsoon season. The locations of the field data are shown in Figure 3-5.

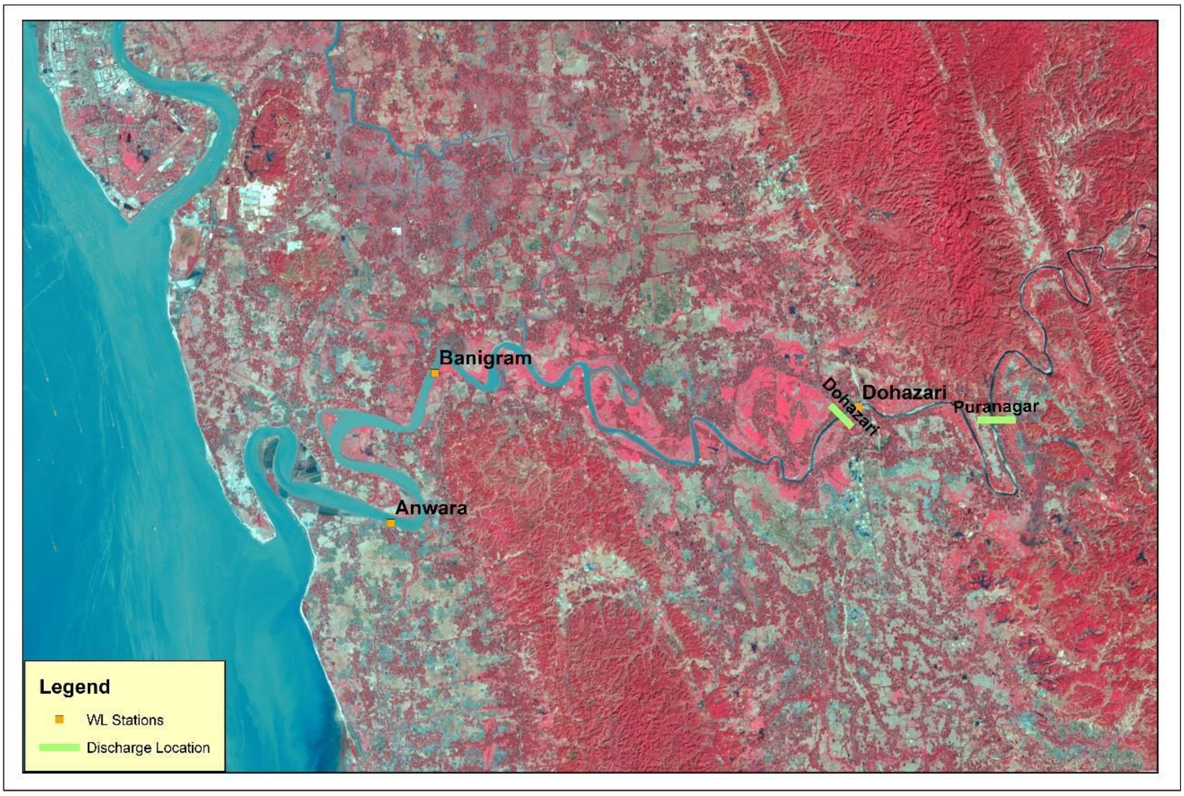

Figure 3-5 Discharge and water level locations for Sangu meso-scale model.

3.3.1 HD calibration 2018

The MIKE 21C model has been run for one year (2018), and the calibration has been done in the measured locations. As there is no monsoon data, we calibrate the model with the available dry season data only. The locations are Anowara and Dohazari for water level, Dohazari for discharge. The plots are shown below. Also, the collected data from BWDB at Banigram station has been plotted against the model result, and the plot has been shown.

The model simulated water level data for 2018 has been plotted against the observed water level station data of Anowara and Dohazari, in Figure 3-6 and Figure 3-7 respectively. The observed discharge value in the Dohazari has been plotted with the simulated discharge and found considerable matches, shown in Figure 3-8.

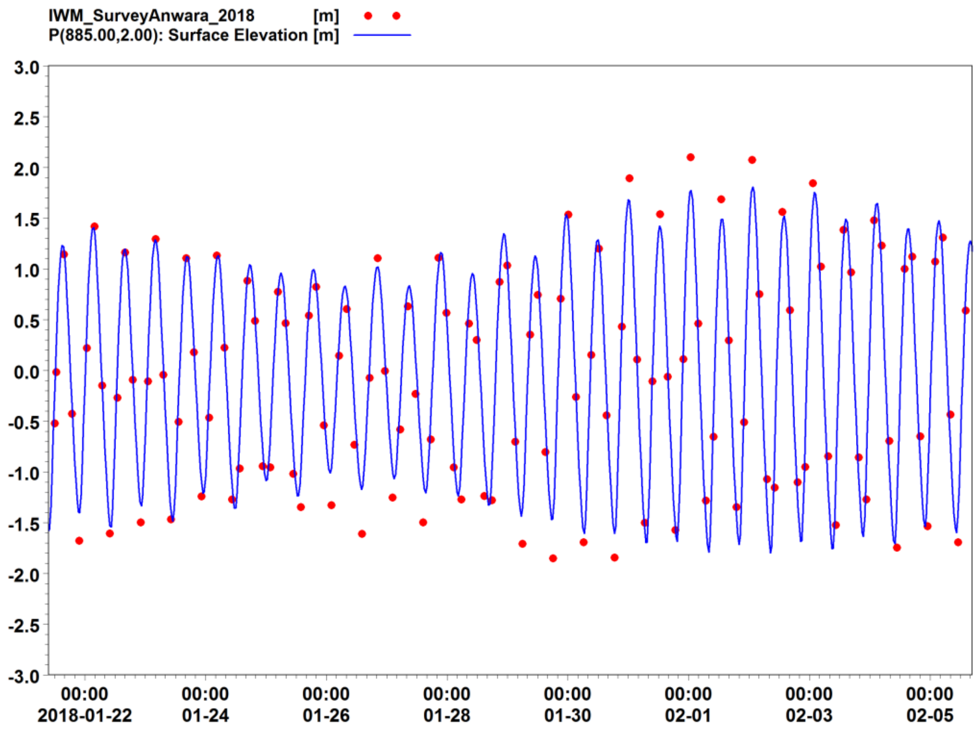

Figure 3-6 MIKE 21C hydrodynamic model calibration plot Anowara (downstream water level).

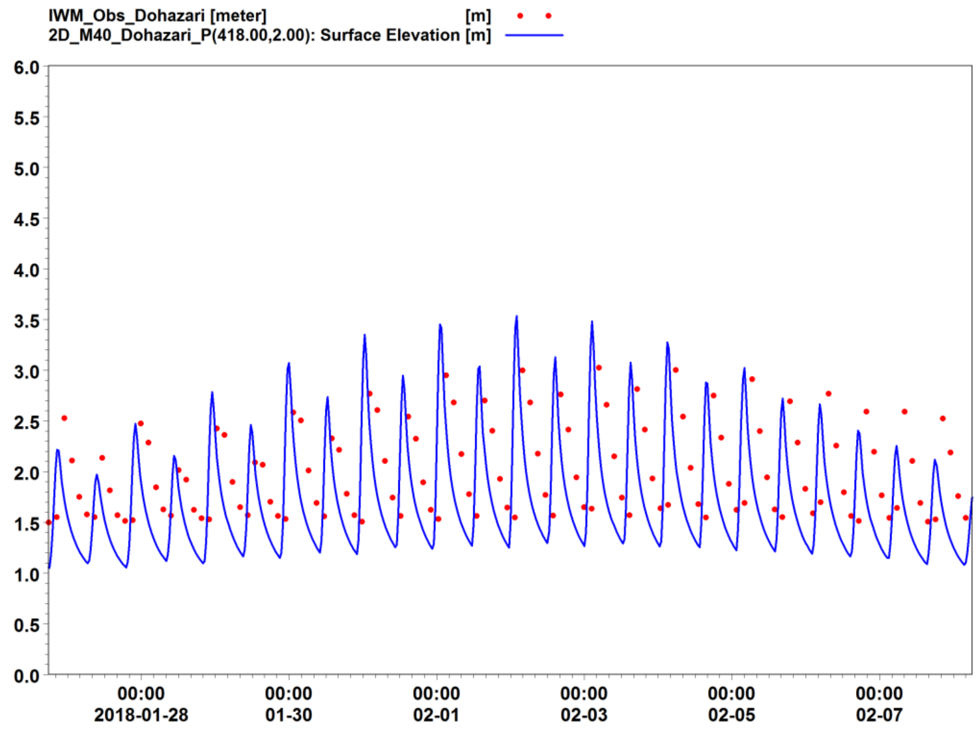

Figure 3-7 MIKE 21C hydrodynamic model calibration plot Dohazari (downstream water level).

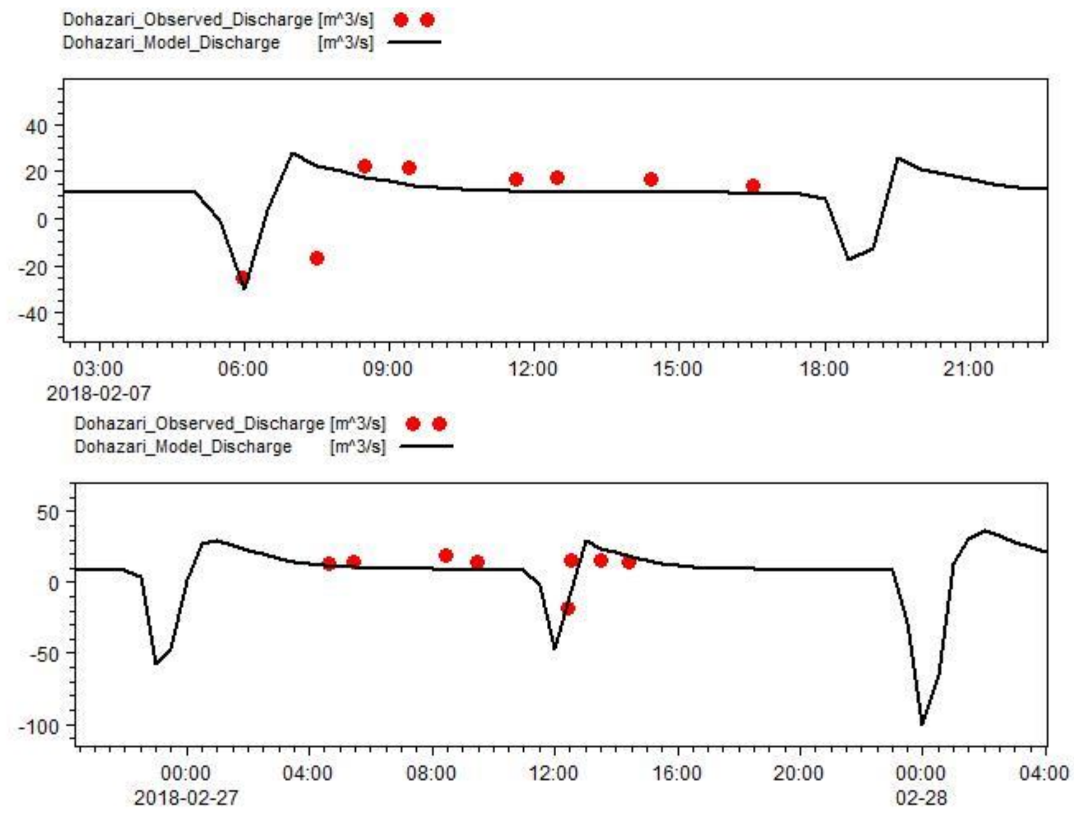

Figure 3-8 Discharge calibration at Dohazari during neap and spring tides in dry period.

3.3.2 HD calibration 2019

The model has also been run in the monsoon, from May to July 2019, as the data is available. The calibration has been shown for discharge in the Sangu bridge, and water level has been calibrated with the data collected from BWDB stations at Banigram and Dohazari.

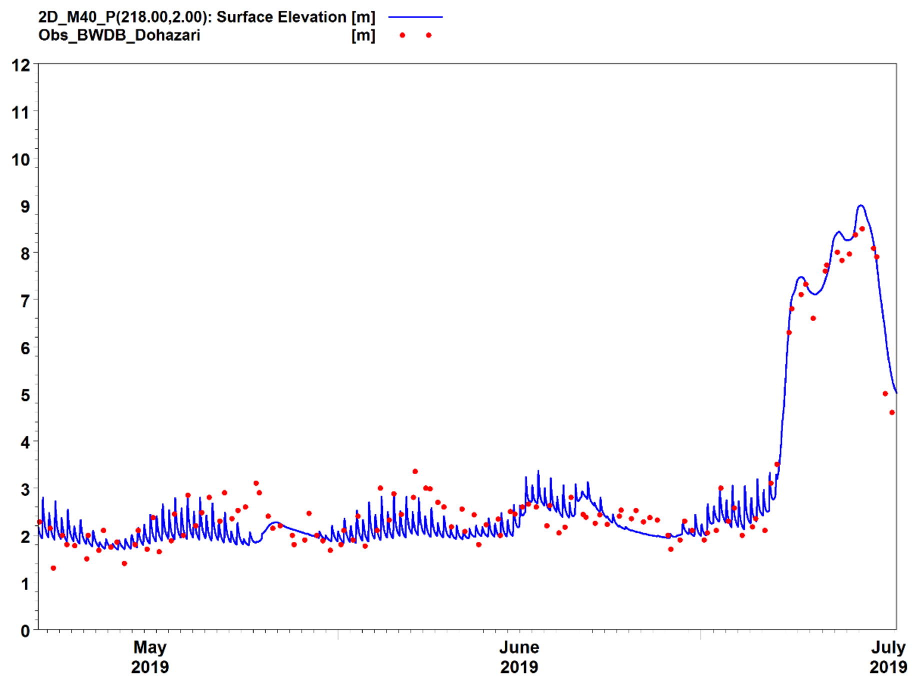

Figure 3-9 MIKE 21C hydrodynamic model calibration plot water level at Dohazari May to July 2019.

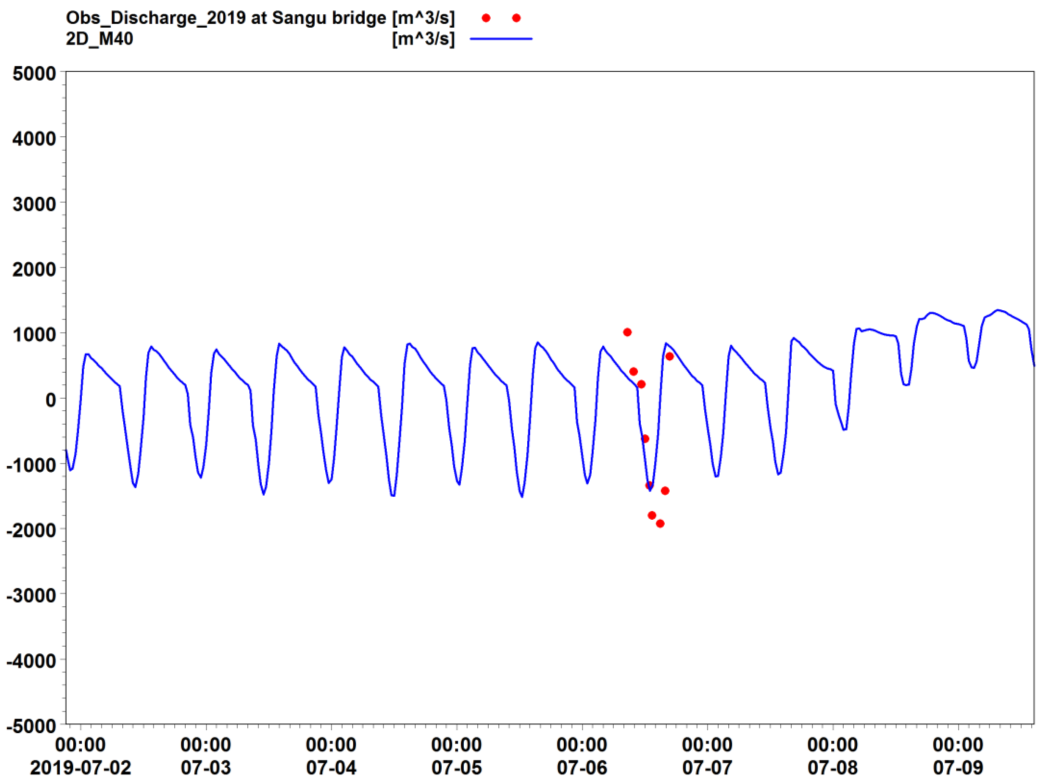

Figure 3-10 MIKE 21C hydrodynamic model calibration plot Discharge at Sangu bridge July 2019.

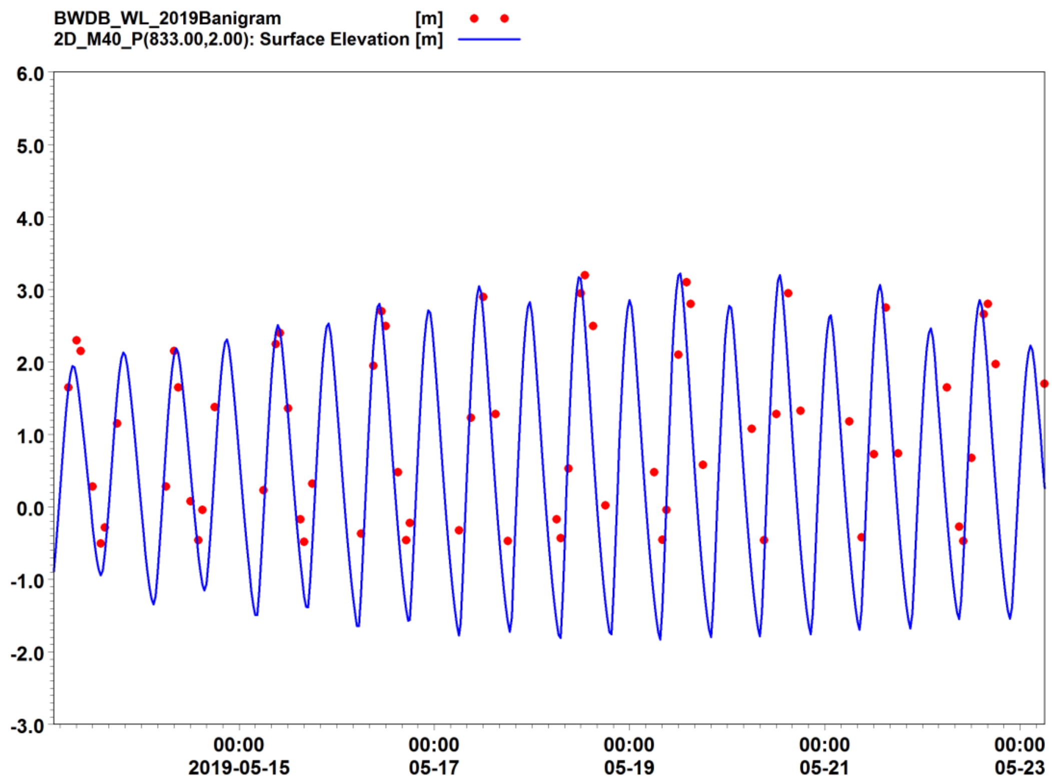

Figure 3-11 MIKE 21C hydrodynamic model calibration plot water level at Banigram May 2019.

3.4 Sediment model

The bed samples show that Sangu consists of mainly sand. A 1-fraction sand model was adopted. The sand is modelled as a non-cohesive fraction with the following parameters:

Grain size = 0.25 mm

Porosity = 0.35

Relative density = 2.65

Critical Shields parameter, θc = 0.056

Transverse slope coefficient = 2.5

Transverse slope power = 0.5

Longitudinal slope coefficient = 5

Bed and suspended load calibration factors = 2,2

The sediment transport formulas of van Rijn (1984a and 1984b) were used for bed-load and suspended load.

3.5 Sediment transport boundary conditions

The upstream boundary condition is the most important. However, we do not have any good SSC data to apply in the model as a boundary, and therefore we used the dz/dt=0 at the upstream end.

We have used SSC=0 at the downstream end as there is no import of sand from Bay of Bengal and all the sand comes from upstream only.

3.6 Sediment transport calibration

The available data is not enough to make the sediment transport calibration with the model results. Moreover, dry season data is available only for two specific days. Dry season sediment concentrations do not tell a lot about the sediment transport; monsoon season observations are much more informative.

3.7 Validation against observed bed level changes

The morphological model was calibrated by hindcasting the bathymetry development 2018-2020.

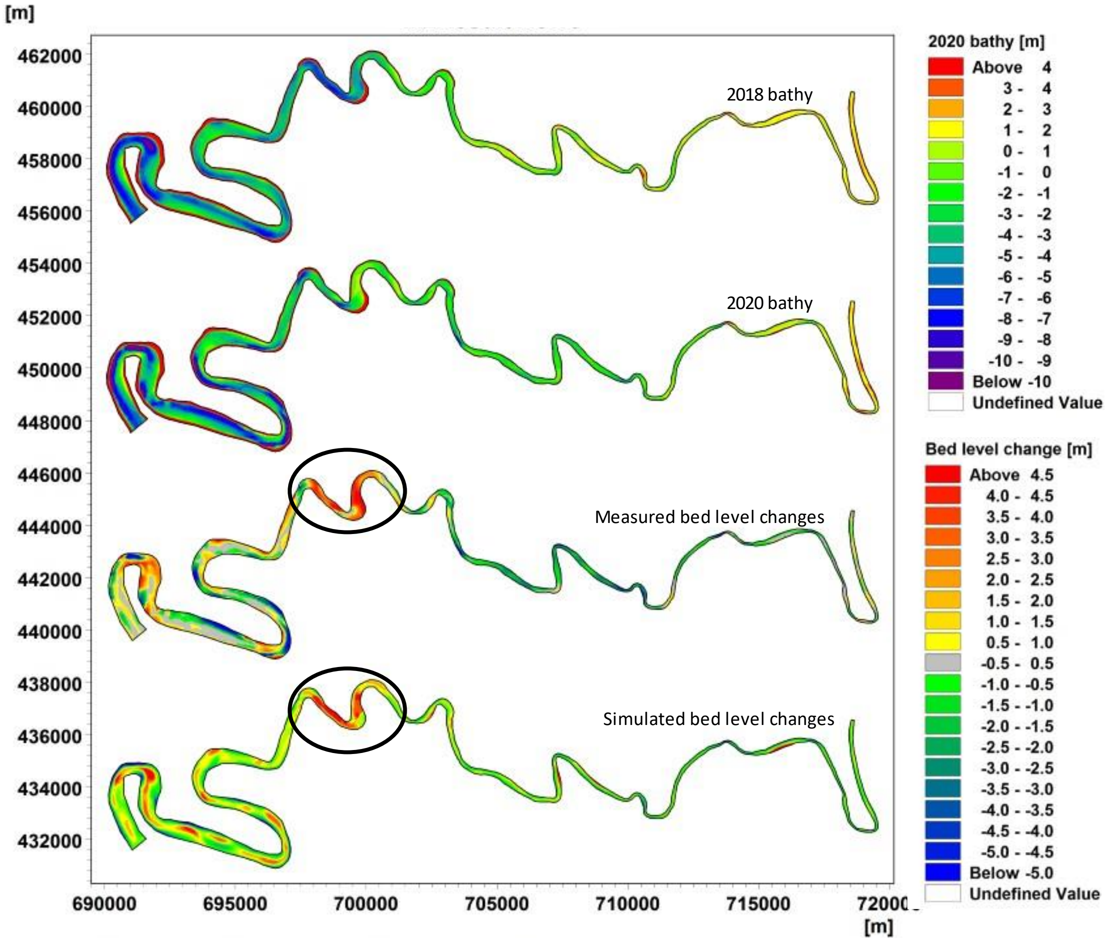

Figure 3-12 Morphological hindcast results 2018-2020, from top: 1) Initial bathymetry (January 2018), 2) Final bathymetry (August 2020), 3) Observed bed level changes (difference between 2018 and 2020 bed level), 4) Simulated bed level changes (2018 to 2020).

The simulated bed level changes match with the observed bed level changes (difference of bathymetry from 2018 to 2020). Around BTM easting 700,000 m, both results show a lot of depositions. In Figure 3-12, the black ellipse has marked the deposition area. Overall, the pattern of the bed level changes shows a considerable level of similarity.

3.8 Validation against observed bulk volume curves

The 2018-2020 bulk volume curve shows the width-integrated morphological changes accumulated along the river axis, which is useful for evaluating the longitudinal sediment transport calibration obtained from the hindcast. The local bulk volume in the curve hence represents the upstream accumulated erosion/deposition. The bulk volume curve does not say anything about the transverse sediment transport calibration.

The bulk volume curve is useful for evaluating erosion and deposition in a more integrated manner compared to local erosion and deposition. The bulk volume increases if deposition takes place and vice versa.

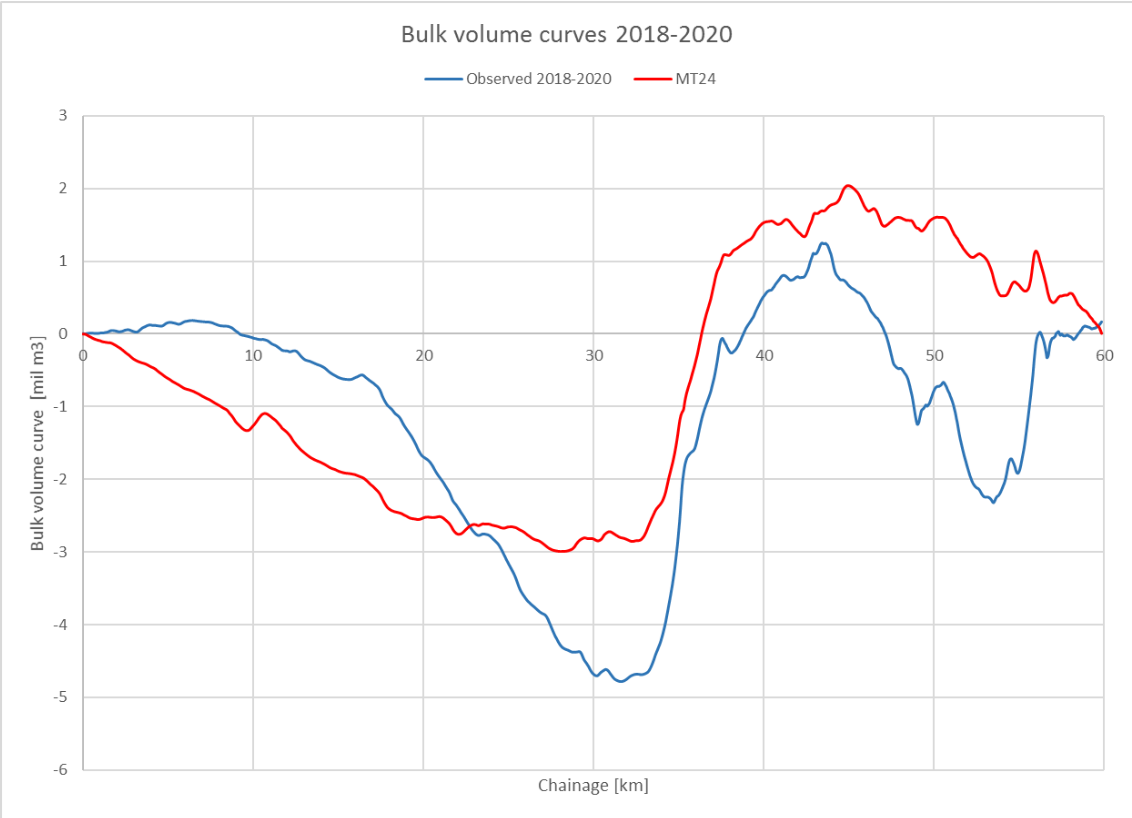

Figure 3-13 Comparison of observed 2018-2020 and simulated 2018-2020 bulk volume curves. The pattern looks similar though the value may differ.

The bulk volume curves are compared in Figure 3-13.

The observed bulk volume curve shows that the bulk volume decreases from upstream until around 32 km (BTM easting 700,000 m). From 32-43 km the bulk volume curve increases significantly, while it decreases again towards 55 km, and finally stays neutral in the last 5 km until the outlet. In other words, erosion takes place over the first 32 km, deposition from 32 to 43 km, erosion from 43 to 55 km, while 55-60 km is neutral.

The simulated bulk volume curves match the observations very well.

The observed volume curves end around zero, which means that during the hindcast period the river exhibited mainly redistribution of sediment, which is also reflected in the simulated bulk volume curves.

Bank erosion was not included in the sediment budget. The main reason for this was that the sediment properties of the banks were unknown and could very well consist of silt and clay, which would not contribute to the sediment budget.

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:

$E_h = 10^{-6}$

$h_c = 5$ m

The calibration result is presented and discussed in the following.

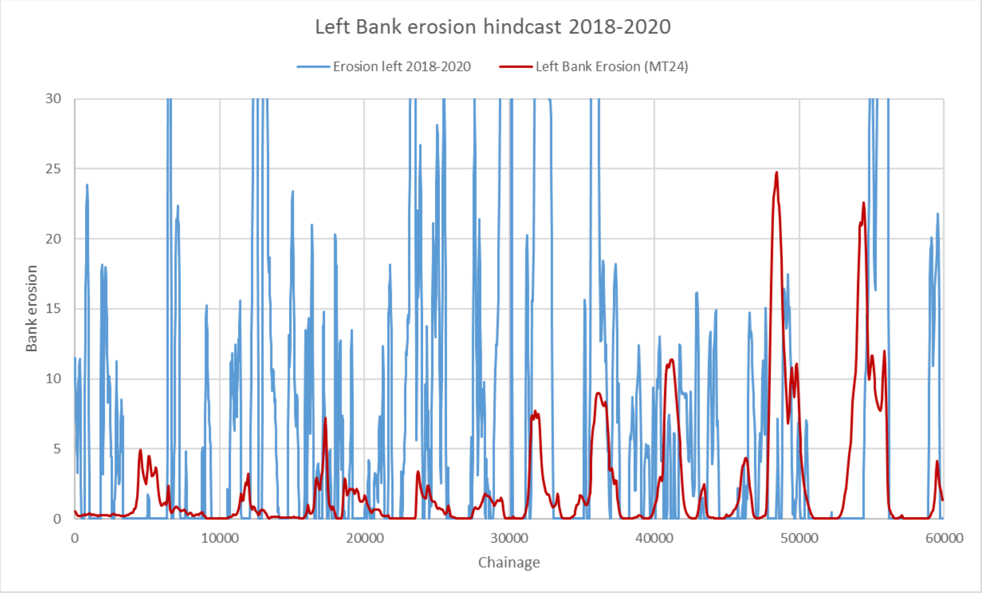

Figure 3-14 Observed and simulated bank erosion 2018-2020, comparison along the left bank.

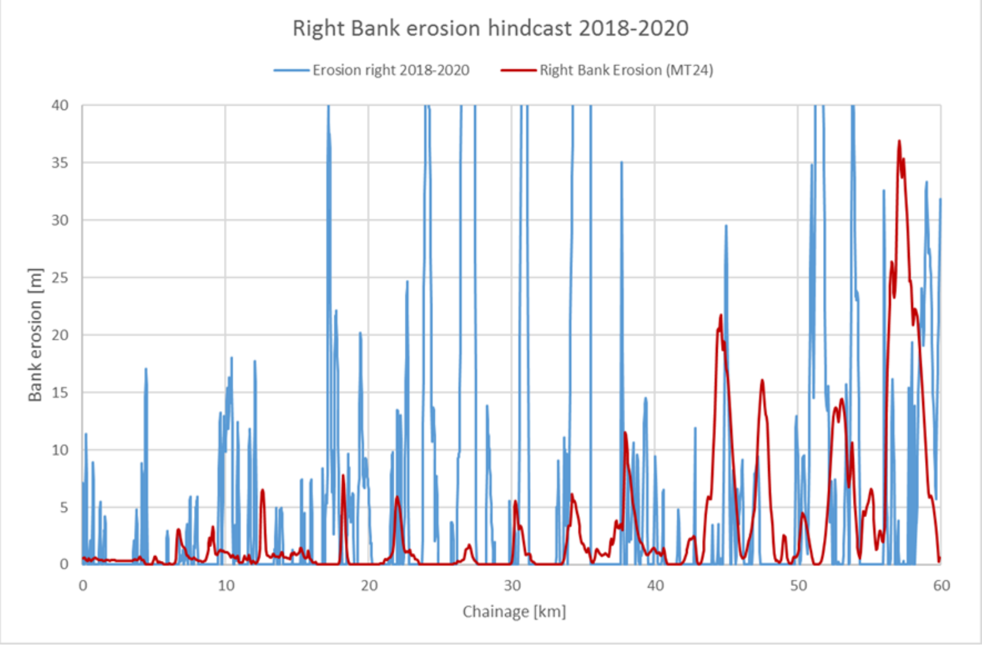

Figure 3-15 Observed and simulated bank erosion 2018-2020, comparison along the right bank.

Using the above value, we have made the bank erosion model for Sangu River. Sangu River is flashy. High-water flow and current velocity during monsoon cause riverbank erosion. Downstream reaches of the Sangu River are meandering, and helical flow in the meandering bank causes erosion of the outer bank. Moreover, deforestation process increases runoff that carries sediments from upstream to downstream and is associated with damage of vegetation and also increases the risk of landslides.

The observed and simulated bank erosions along the river chainages are compared in Figure 3-14 and Figure 3-15. Keep in mind that the initial bank line was 2018 along with a 2018 bathymetry. It is difficult to obtain the bank erosion accuracy. Moreover, huge amounts of data are required to make the detailed bank erosion prediction model.

4 Model applications

No scenario simulations were made for the Sangu model.

5 Conclusions

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

Three years' bathymetry data is available, i.e. 2005, 2018 and 2020. The 2005 data is too coarse for 2-dimensional modelling, while the 2018 and 2020 data are @500m interval. The Sangu River was modelled using the 2018 bathymetry as initial condition in the morphological model.

There are three water level stations in the river reach with longer records over time. In Dohazari and Bandarban, the discharge data is available. If discharge data is not available, the rating curve is used to calculate the discharge. The name of the stations is Banigram, Dohazari and Bandarban. For project connections, IWM has collected data for more than these stations, i.e. Bailtoli near Sangu (Shonkho) bridge, Anowara downstream of Banigram. The historical data is available for the three stations. The latest data up to 2020 is available and measured in different project connections which have been utilized for the model calibration and validation.

The samples are collected from the main river channel and both banks across the same cross-section. The value of median diameter of collected bed sample, i.e. d_{50}, is calculated for each sample. The bank materials are dominated by sand with some gravel (particle size varies from 0.063 to 4mm). Riverbed materials collected from Sangu River reveal that sand is predominant. The average particle size (d_{50}) of the sediment varies from 0.17 mm to 0.34 mm in most locations of the Sangu riverbed.

In dry season, SSC observations are available for Dohazari station. The data is available only for two days, i.e. one day in January and one day in February of 2018. It is noted that both days are in the dry season, while the river is highly seasonal with very low flows in the dry season and high flows in the monsoon. Monsoon SSC data would be more valuable, but are not available.

Suspended sediment particle size distribution data is not available for the Sangu River. However, such data is less important for a sandy river compared to a river dominated by silt. Hence, the lack of such data is not a serious issue for the Sangu River.

For the inspection of erosion, Landsat imagery was acquired for the period of 1988-2019. IWM engineers digitized the bank lines 1988 to 2019, typically every 5 year, to have the data available for the model study. Moreover, the latest Sentinel image has been analysed for the available years, i.e. 2016 to 2020.

Many bank protection works have been found in both banks of the Sangu River. BWDB is continuously working on the bend erosion.

To simulate the morphological model with different hydrological events, the bathymetry data was superimposed on the curvilinear grid along with flow discharge and water level data in the upstream and downstream part of the model, respectively. The bathymetry of the model has been prepared based on data from the IWM bathymetric survey carried out during 2018. This bathymetry has been used as input (initial bed level) to the model.

The upstream boundary has been extracted from the calibrated one-dimensional Eastern Hilly Regional Model (EHRM). In the hydrodynamic model, the upstream boundary comes from the EHRM model as discharge, and downstream the water level data has been extracted from the updated (2018 and 2019) Bay of Bengal model. There are no significant tributaries or distributaries along the Sangu River model. Hence the model only contains the upstream discharge and downstream water level boundary conditions.

The resistance calibration was partly inherited from the MIKE 11 EHRM. The resistance coefficient used is Manning M=40 $m^{1/3}/s$. For dry season, calibration has been done for 2018 and for monsoon 2019, according to the available data.

The MIKE 21C model has been run for one year (2018), and the calibration has been done in the measured locations. As there is no monsoon data, we calibrate the model with the available dry season data only.

The model has also been run in the monsoon, from May to July 2019, as the data is available. The calibration has been shown for discharge in the Sangu bridge, and water level has been calibrated with the data collected from BWDB stations at Banigram and Dohazari.

A 1-fraction sand model was adopted using d_{50} = 0.25mm. The other parameters used in the model are porosity = 0.35, relative density = 2.65, critical Shields parameter, θc = 0.056, transverse slope coefficient = 2.5, transverse slope power = 0.5, longitudinal slope coefficient = 5 and bed-load and suspended load calibration factors = 2 and 2. The sediment transport formulas of van Rijn were used for bed-load (van Rijn, 1984a) and suspended load (van Rijn, 1984b).

The morphological model was calibrated by hindcasting the bathymetry development 2018-2020. The simulated bed level changes match with the observed bed level changes (difference of bathymetry of 2018 and 2020). Around BTM easting 700,000 m, both result show a lot of depositions. Overall, the pattern of the bed level changes shows a considerable level of similarity.

The observed bulk volume curve shows that the bulk volume decreases from the upstream end until around 32 km (BTM easting 700,000 m). From 32-43 km the bulk volume curve increases significantly, while it decreases again towards 55 km, and finally stays neutral in the last 5 km until the outlet. In other words, erosion takes place over the first 32 km, deposition from 32 to 43 km, erosion from 43 to 55 km while 55 to 60 km are neutral.

The simulated bulk volume curves match the observations very well. The observed volume curves end around 0, which means that during the hindcast period the river exhibited mainly redistribution of sediment, which is also reflected in the simulated bulk volume curves.

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], Eh a non-dimensional calibration parameter, V is the near-bank flow velocity [m/s], h is the near-bank water depth [m], and hc is 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:

$E_h = 10^{-6}$

h_c = 5 m

Using the above value, we have made the bank erosion model for Sangu River. Sangu River is flashy. High-water flow and current velocity during monsoon cause riverbank erosion. Downstream reaches of the Sangu River are meandering, and helical flow in the meandering bank causes erosion of the outer bank. Moreover, deforestation process increases runoff that carries sediments from upstream to downstream and is associated with damage of vegetation and also increases the risk of landslides.

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