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)

Micro-Scale Modelling

Interim Report: Modelling of TRM Operation 2D

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ACRONYMS AND ABBREVIATIONS

BoB	Bay of Bengal
BWDB	Bangladesh Water Development Board
CEIP-	Coastal Embankment Improvement Project
DEM-	Digital Elevation Model
FM-	Flexible Mesh
GBM	Ganges, Brahmaputra and Meghna
HD-	Hydrodynamic
IWM-	Institute of Water Modelling
KJDRP	Khulna-Jessore Drainage Rehabilitation Project
SLR-	Sea Level Rise
SSC-	Suspended Sediment Concentration
SWRM-	South West Region Model
TRM	Tidal River Management
WL	Water Level

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 forms 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 deltas on the planet. The coastal land mass is formed by the interaction of large volumes of sediment laden water with the moderate to high tides of the Bay of Bengal. Figure 1.1 shows the tidal limits in the Bengal Delta.

Land in the coastal zone is built up by the deposition of river sediments among the mangroves in one of the largest mangrove forests in the world. The deposits of sand, silt, clay and peat form the land mass, which despite subsidence due to continuous consolidation of layers many kilometres deep, is kept just below the level of the highest tides by the continuing deposition of sediments that are trapped among the mangroves.

The coastal zone of Bangladesh spans over 710 km of coastline and is subject to multiple threats. 62 % of the coastal land has an elevation less than 3 meters above mean see level. With a sediment supply of the order of 1 billion tons per year, this is the delta with the largest sediment supply in the world. This leads to accretion of the land area in the coastal zone (5-10 km^2/year, mainly in the Meghna Estuary). 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 in the deepest strata that give rise to other changes in ground level.

The coastal lands, 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 made possible the reclamation of large tracts of land for agriculture from 1960 onwards. Polder building proceeded continuously until today. We now have 1.2 million hectares reclaimed in 139 active polders in the coastal zone of Bangladesh, see Figure 1.2.

In over half a century of its existence, 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 the polders

- Changes in tidal hydrodynamics and related river erosion and siltation in the peripheral rivers of polders
- Increasing vulnerability to cyclones and storm surges

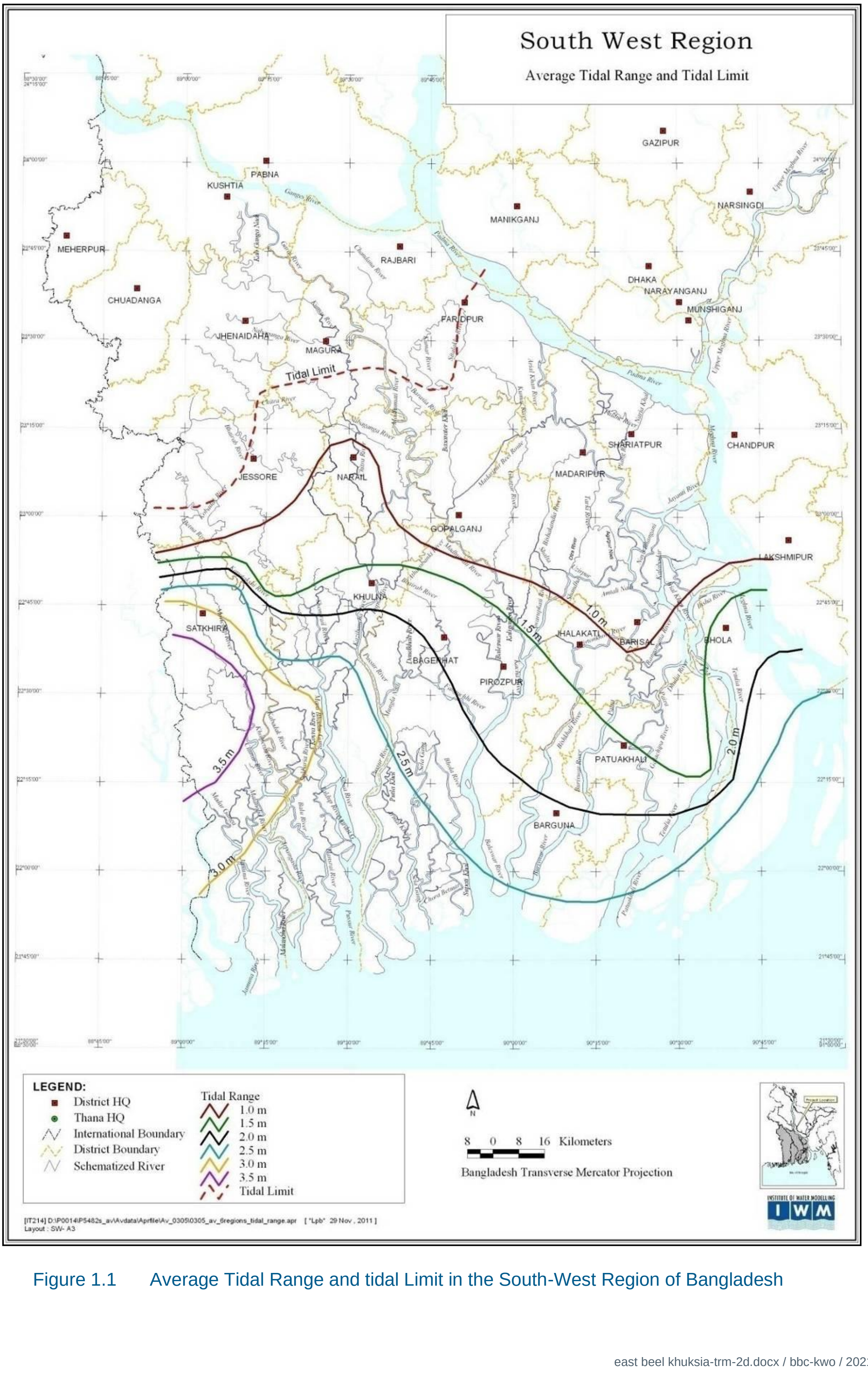

Figure 1.1 Average Tidal Range and tidal Limit in the South-West Region of Bangladesh

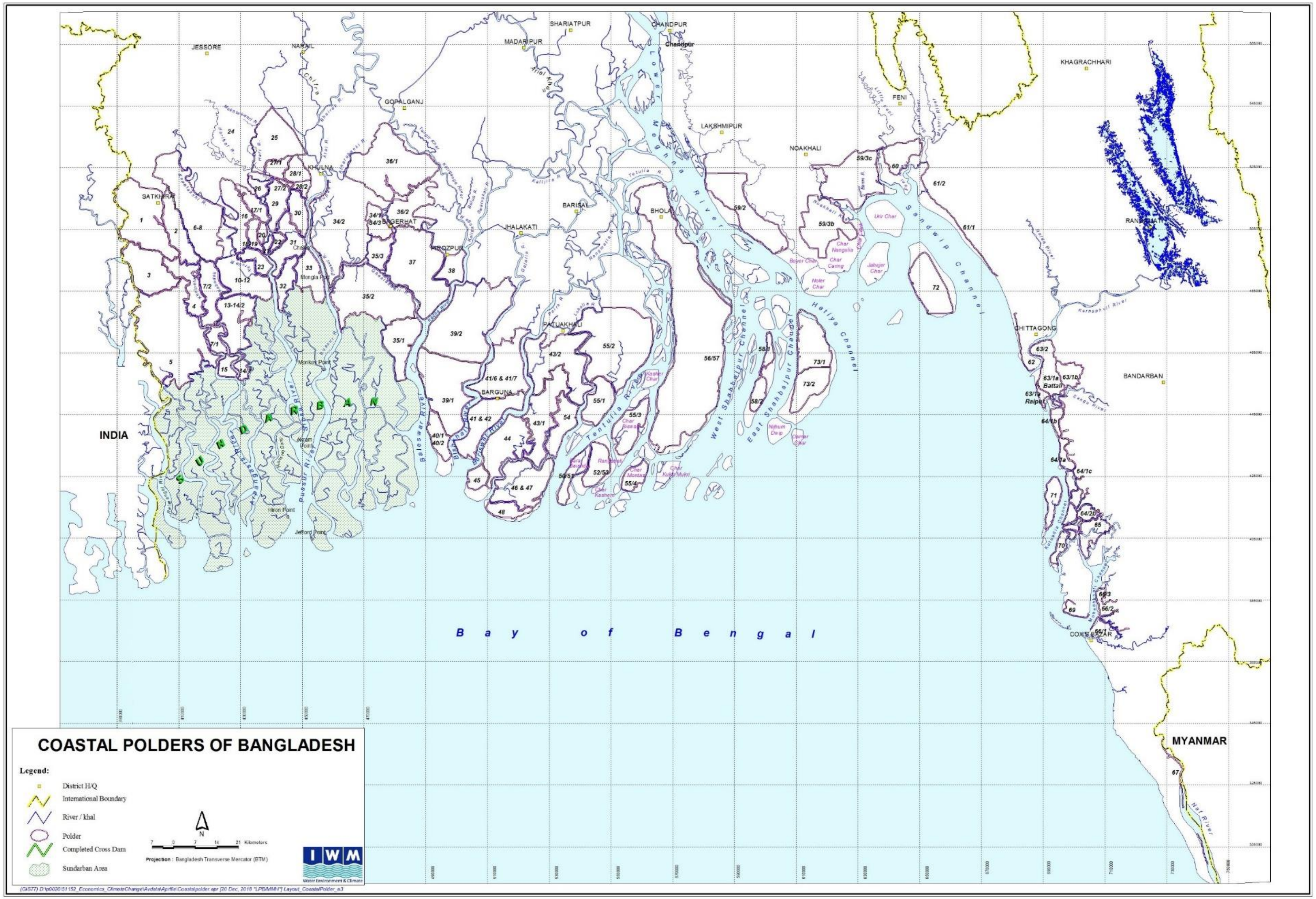

Figure 1.2 Coastal Polders of Bangladesh

The disasters resulting from two major cyclones Sidr (2007) and Aila (2009) and the unexpectedly high value of the damages caused by these, provoked the World Bank and the Government of Bangladesh to initiate the Coastal Embankment Improvement Programme (CEIP-1), which was to redesign and rebuild the entire polder system, in several phases, to resist the long-term challenges of climate change and other natural phenomena such as:

- Storm Surges, wind and wave attack
- Sea level rise
- Land subsidence
- Changing tidal hydrodynamics and channel network system
- Long term challenges to drainage
- Increasing threats from cyclones and storm surges
- Maintenance and management failures

The objectives of CEIP–1 were:

- *Increase the area protected in selected polders from tidal flooding and frequent storm surges, which are expected to worsen due to climate change and relative sea-level rise*
- *Improve agricultural production by reducing saline water intrusion in selected polders; and*
- *Improve the Government of Bangladesh's capacity to respond promptly and effectively to an eligible crisis or emergency*

The implementation of the first 17 polders of CEIP–1 (see Figure 1.2) brought into stark relief several shortcomings and gaps in our knowledge and understanding of many of the physical phenomena that govern major processes in and the evolution of the Bengal Delta. Recognition of these lacunae resulted in the inclusion of this research study as a component project to support the phased Coastal Embankment Improvement Programme, which was to bring in massive investments over many decades.

1.2 Objectives of TRM Modelling

Tidal River Management (TRM) involves breaching the embankments surrounding the polders allowing tidal flooding of the polders and the associated sediment deposition within the polders as well as erosion of the peripheral rivers due to the increased tidal volume. TRM has for many years been considered a viable way to maintain the drainage capacity of the peripheral rivers and for compensating the impact of subsidence by increasing land level inside the polders through deposition of silt. The key problem with TRM is that the areas inside the polders, which are subjected to tidal flooding cannot be used for the intended purpose of the polders (viz. agriculture), while TRM is ongoing hence the population of the polders must be paid compensation, and likewise alternative livelihood created. An issue with TRM operation is that deposition inside the polders is highly non-uniform (see example in Figure 1.3), hence not the entire area inside the polders may benefit from deposition.

There is thus much to win if TRM operation can be optimised, i.e. accelerate erosion in the peripheral rivers, accelerated deposition within the polders and by ensuring a more uniform deposition pattern. The objective of TRM modelling is to establish a modelling approach that can be used to test alternative TRM operations and identify the most effective operations. The purpose of the modelling presented in this interim report is to explore what will be required in terms of modelling to optimise TRM operation and is based on the application of a state-of-the-art 2D modelling approach.

The TRM operation implemented for East Beel Khuksia will be used as pilot case because ample data are available from the TRM operation of this beel inside Polder 24. The beel and river system of the area is shown in Figure 1.4. In Section 2 of this Report the key data of the TRM operation as well as the available data are described. The key source of data and information used is the reports:

- Monitoring the performance of Beel Kedaria TRM and baseline study for Beel Khuksia. Khulna Jessore Drainage Rehabilitation Project. Final Report. IWM (March 2006), Ref. /1/.
- Monitoring the Effect of East Beel Khuksia TRM Basin and Dredging of Hari River for Drainage Improvement of Bhabodah Area. Khulna Jessore Drainage Rehabilitation Project. Final Report. IWM (July 2007), Ref. /2/.
- Power Point presentation made by Zahirul Haque Khan, Head of Coast, Port and Estuary, IWM at the Dhaka Water Knowledge Days, October 2019.

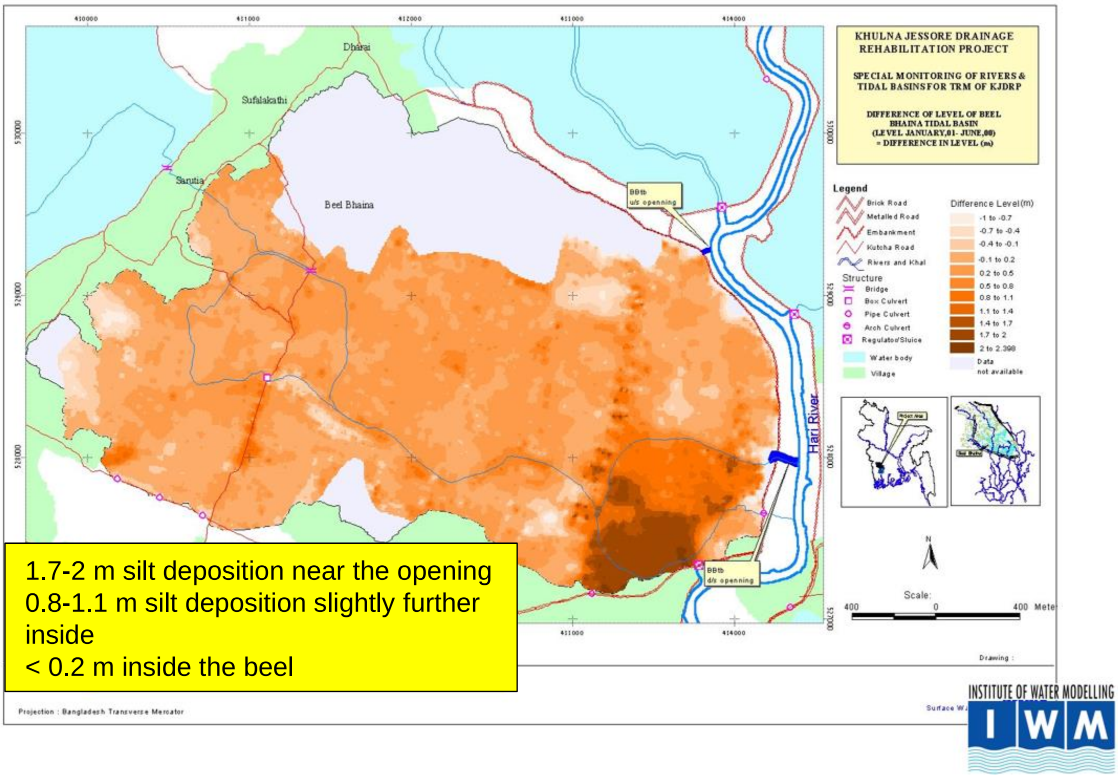

Figure 1.3 Example of non-uniform deposition in a polder subjected to TRM

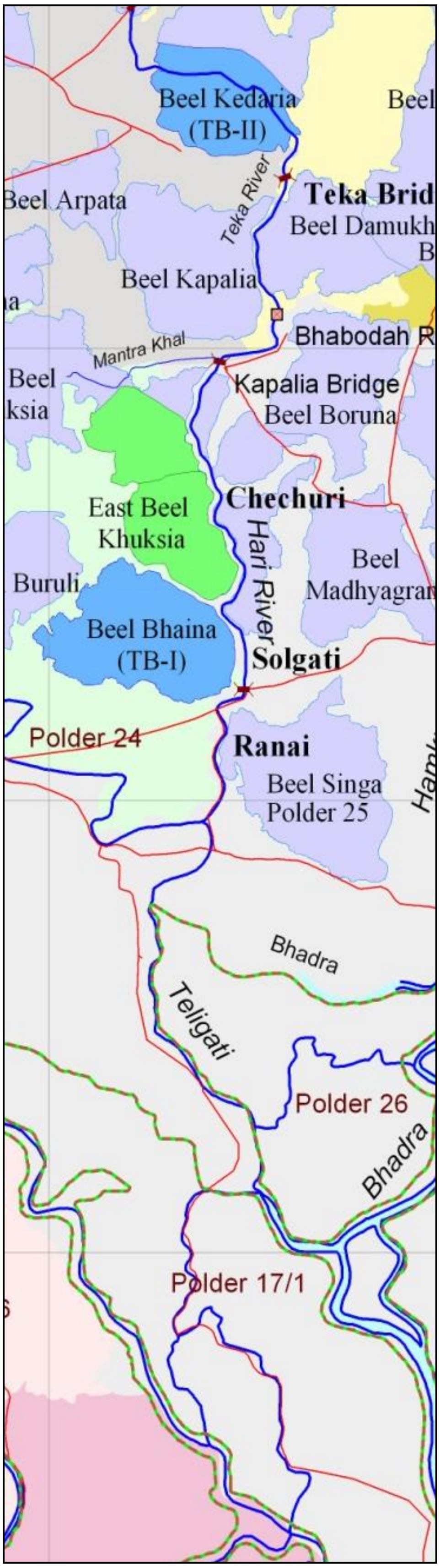

Figure 1.4 Rivers, polders and beels in the study area. Note the location of East Beel Khuksia and Beel Kedaria

2 East Beel Khuksia TRM Operation and Data Available

2.1 Pre TRM Situation

Tidal River Management had been adopted since 1998 in the north-west part of the Khulna-Jessore Drainage Rehabilitation Project (KJDRP) to solve drainage congestion. Beel Bhaina and Beel Kedaria (see Figure 1.4 for location of these polders) were subjected to tidal flooding and created enough tidal volume to maintain the capacity of Teka and Hari Rivers. During the dry season of 2005 TRM operation of Beel Kedaria ceased and the Hari river was rapidly silting up, see Figure 2.1.

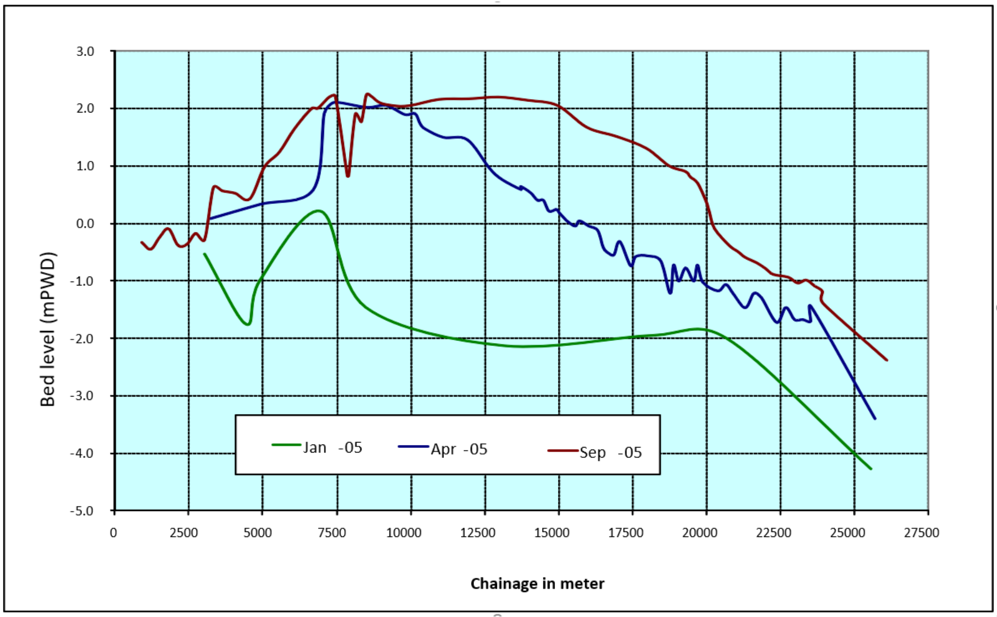

Figure 2.1 Siltation of Hari River after TRM operation of Beel Kedaria was discontinued

The order of magnitude of the deposited sediment from January 2005 to April 2005 can be estimated as follows:

- The average deposition height is about 2 m
- The average width of the river below low water is on average about 20 m, see Figure 2.4
- The length subjected to deposition is about 20 km
- The deposited volume is therefore 800,000 m^3

Assuming an average density of the sediment of 1,000 kg/m^3 (unconsolidated sediment) the weight of the deposited sediment is 800,000 tons, which corresponds to a deposition of about 4,000 tons per tidal cycle.

2.2 TRM Operation

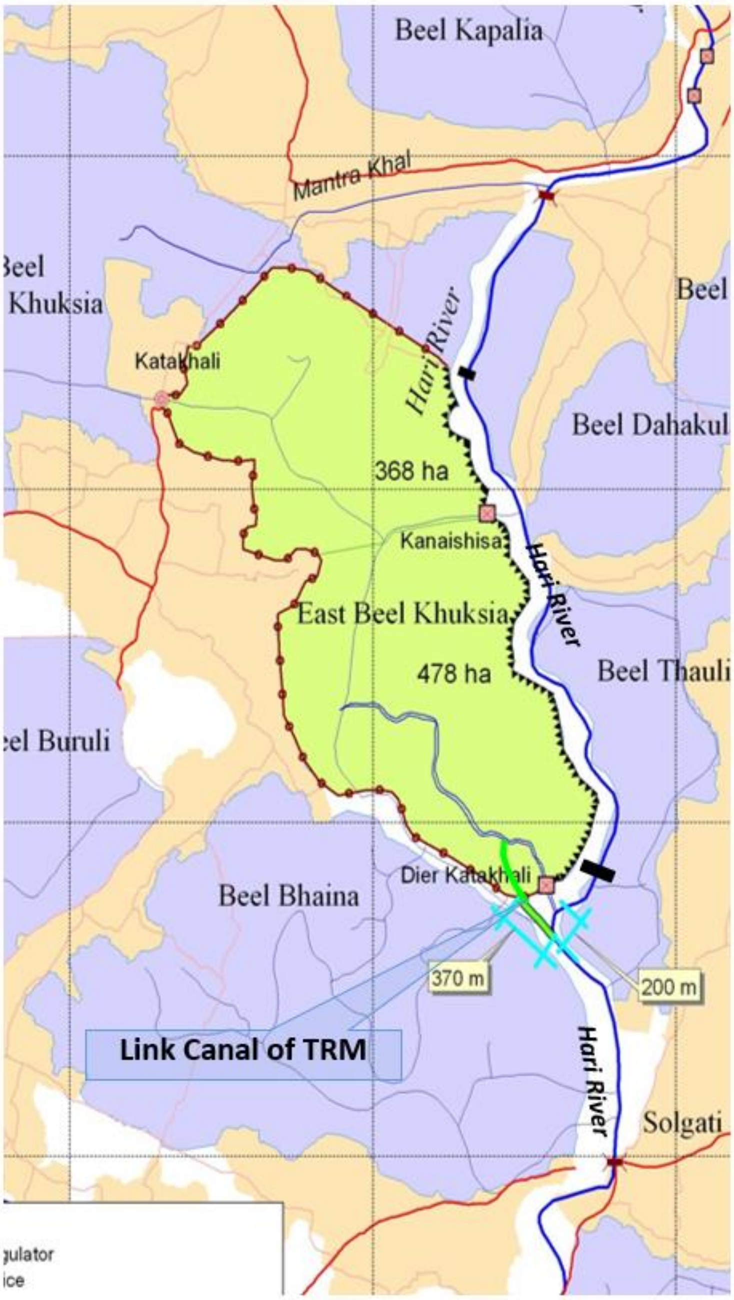

Figure 2.2 East Beel Khuksia with the link canal of TRM at Katakhali Regulator

In response to the lost drainage capacity of the Hari River TRM operation was initiated at the East Beel Khuksia on 30 November 2006 by opening a link channel to the Hari River, see Figure 2.2 for location of the link channel. During the period August 2006 to April 2007 dredging of the Hari river was also undertaken. The TRM operation and dredging led to a significant increase of the drainage capacity of the Hari river as evidenced by the development of a cross-section in the Hari River shown in Figure 2.3. In Figure 2.3, it should be highlighted that the major part of the enlargement of the cross-section took place after the dredging operation ceased (i.e. from May 2007 and onwards) thus through natural erosion.

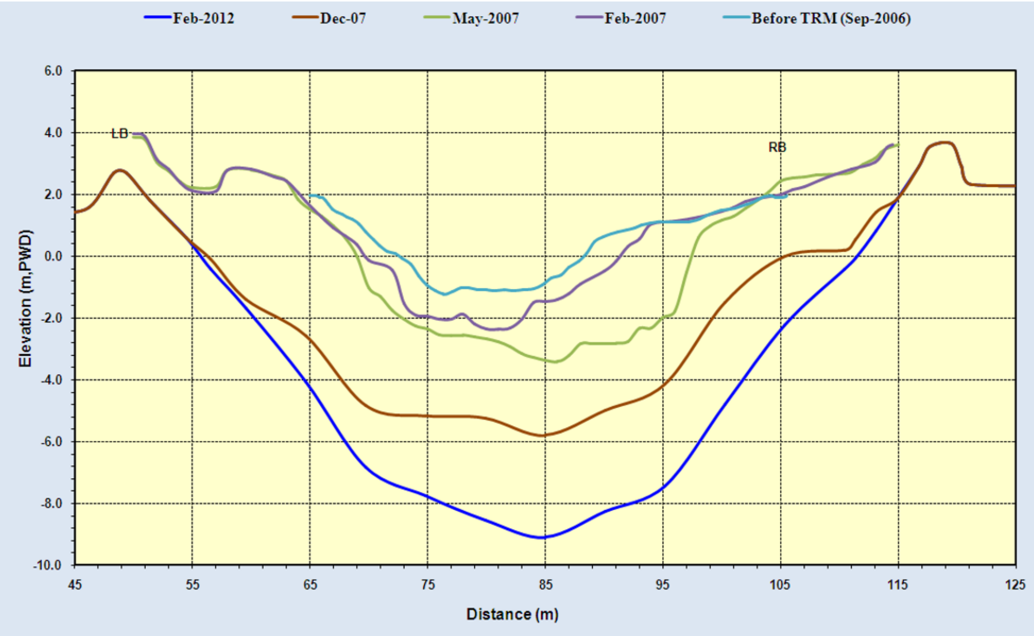

Figure 2.3 Development of a cross-section in the Hari River. From February 2007 to May 2007 both dredging and erosion take place, while after May 2007 only erosion

2.3 Data Available

IWM has made the following data available:

- The cross-section database for the SWRM contains cross-sections from several survey campaigns. For the Hari River cross-sections are available from surveys carried out in 2008 and 2016, where the 2008 cross-sections are generally significant deeper and wider than those surveyed in 2016 (thus there has been deposition from 2008 to 2016).

- Cross-sections in the Hari River at Chainage 11662, 17223 and 24279. All surveyed in February 2004, May 2004 and April 2005. The latter set is after Beel Kedaria TRM operation has ceased. A sample cross-section (at Chechuri – approx. chainage 12412) is shown in Figure 2.4. From February to May 2004 the riverbed is eroding slightly probably due to TRM operation at Beel Kedaria, while significant deposition takes place between May 2004 and April 2005 due to the terminated TRM operation.

- 31 Cross-sections in the Hari River surveyed November 2006 thus immediately before TRM operation of East Beel Khuksia commenced. These data should be processed (and checked) and potentially be included in the model setup.

- Sediment concentration data for a full tidal cycle from two locations inside the East Beel Khuksia during spring tide in May 2007 (thus during TRM operation).

- Sediment concentration data for three full tidal cycles representing spring, neap and spring tides (in May 2007) in Hari River at chainage approx. 19662.

- In connection with the sediment measurements the total depth at the measuring points were recorded: From these data it's possible to derive the tidal range at the measuring points.

- Two full set of topography of East Beel Khuksia from February (pre-TRM operation) and May 2007. We have calculated the accumulated sediment volume to 1.2 mill m^3, but this estimate is somewhat uncertain. In fact, the sample density and quality of data may not be good enough to establish reliable 2D model setups based on these data sets of polder topography.

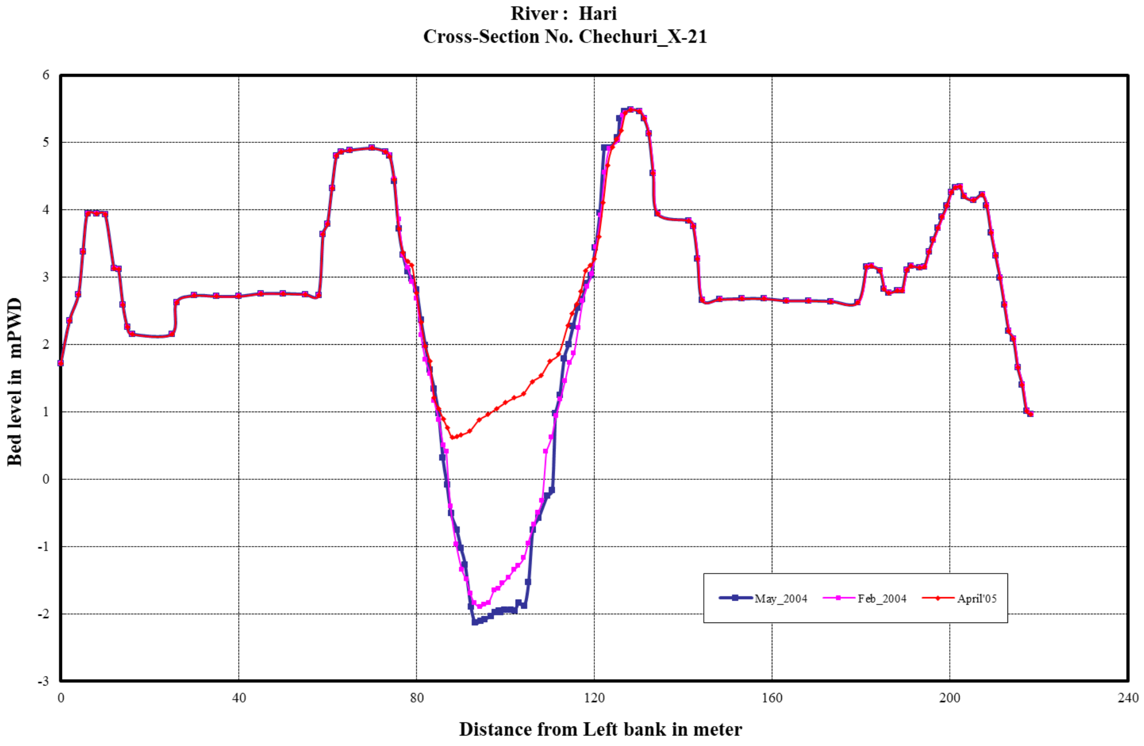

Figure 2.4 Observed cross-sections in Hari River at Chainage 12412 (location of Chechuri shown on Figure 1.4)

3 Model Development (MIKE 11)

3.1 Introduction

The purpose of modelling presented in this interim report is to explore what will be required in terms of modelling to optimise TRM operation and is based on the application of a very simple 1D modelling approach. The model simulates hydrodynamics and advection-dispersion of suspended sediment represented by one (representative) size fraction only. Erosion and deposition are defined as sources and sinks in the advection-dispersion model and calculated as simple/standard functions of the cross-sectional average bed shear stress (thus a standard cohesive sediment modelling approach). There are thus no 2D representation, which is likely to be important in the polders/beels, nor morphological feedback (impacts from erosion and deposition on the flow pattern), which may be important in the peripheral rivers.

IWM availed a curtailed version of the South-West Regional Model (SWRM). The layout of the curtailed model is shown in Figure 3.1. East Beel Khuksia is part of Polder 24. Polder 29 is one of the selected polders in this study. The model boundary conditions are the corresponding simulated values from the full SWRM. Boundary conditions are available for the period 4th January 2011 to 31st May 2012, only. For this particular period there are no available observations of neither water levels nor sediment concentration/transport from the study area.

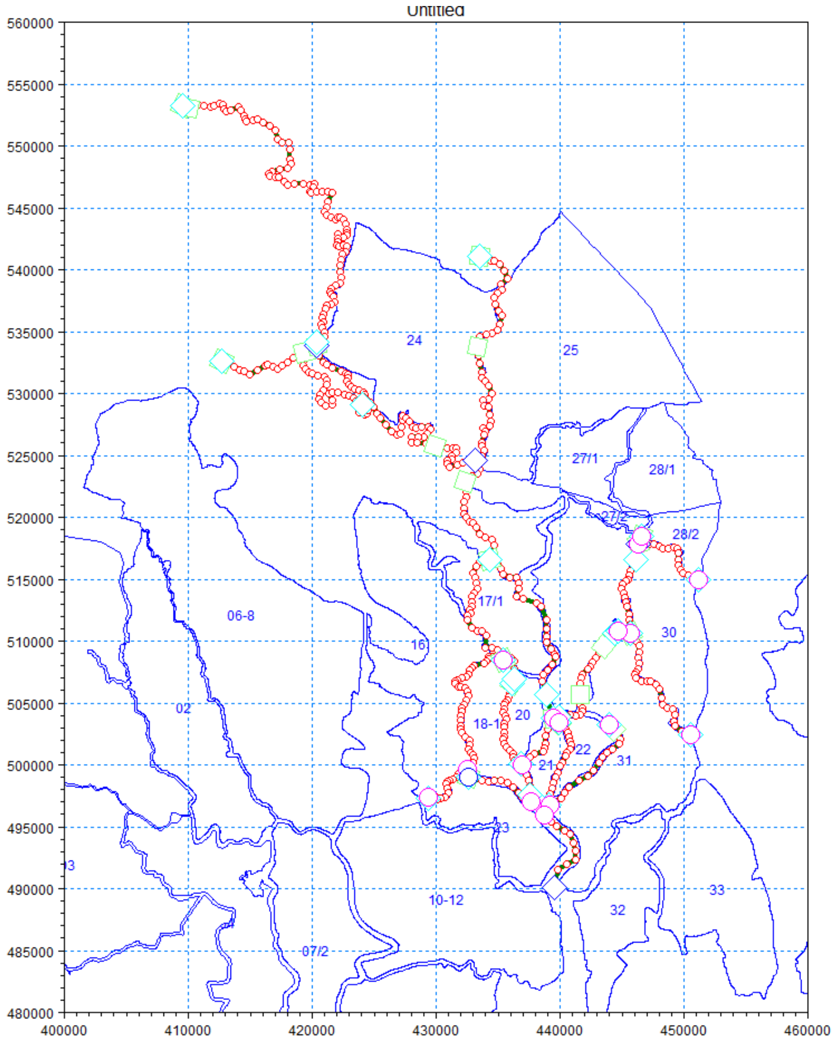

Figure 3.1 Curtailed SWRM setup with polder map.

3.2 Model Adjustments.

For the modelling of the East Beel Khuksia TRM operation the model has been further curtailed. Everything below the junction of Lower Bhadra, Habarkhali and Deluti Rivers has been removed. Implicitly, this implies that it has been assumed that the tidal signal at this junction is not affected by the TRM operation at East Beel Khuksia. The purpose of this further reduction of model extend is to increase the speed of simulations and to avoid having to consider the sediment dynamics below the junction. In addition, the East Beel Kuksia has been added to the model setup through a short (100 m long) link channel with a hydraulic structure in the middle. The hydraulic structure can be adjusted to allow free inflow and outflow (representing TRM operation), only outflow (inserting a flap gate to represent normal polder operation), completely closed or any other operation that could be relevant to investigate for optimisation of TRM operation.

The final model setup is shown in Figure 3.2.

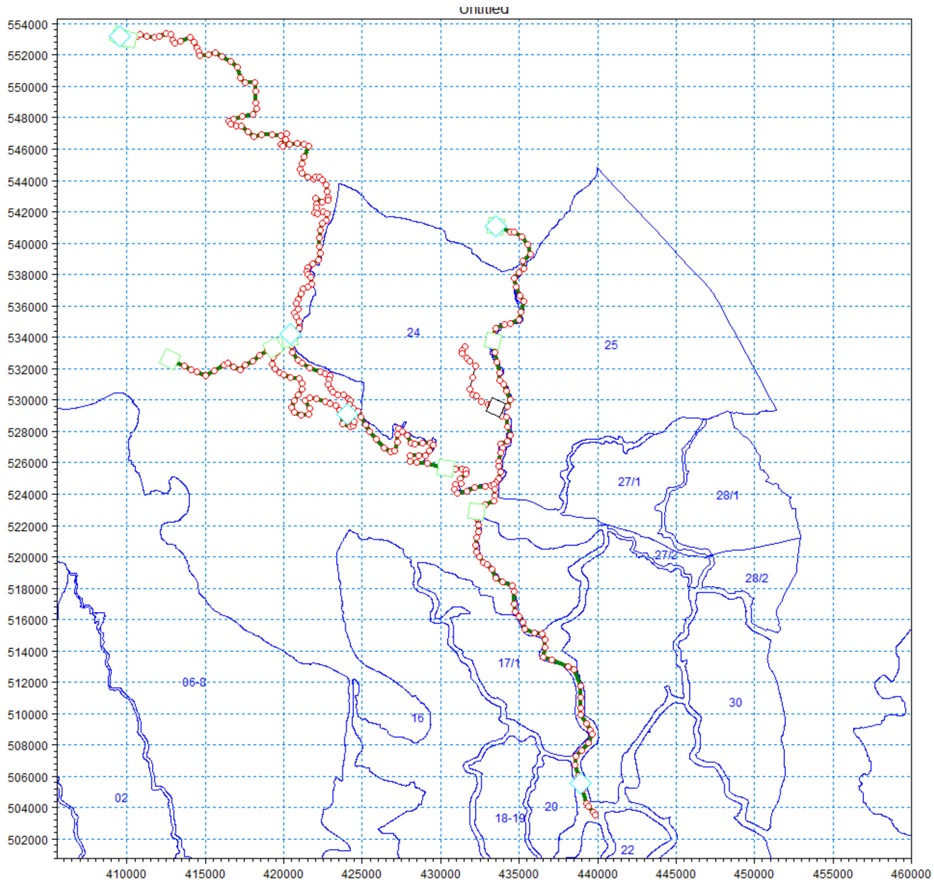

Figure 3.2 The Hari sub-model with East Beel Khuksia included.

MIKE 11 will insert interpolated or extrapolated cross-sections at junctions and external boundaries (cul-de-sac branches) if no (surveyed) cross-section is given at these locations. This can lead to very short space steps between surveyed and interpolated cross-sections which in turn may require the use of a small time step. To avoid this type of interpolation/extrapolation of cross-sections the following modifications have been introduced:

- U-BHADRA has been shortened and now starts at first available cross-section at chainage 250 (was chainage 0, where no cross-section is available)
- Move junction from U-BHADRA from Chainage 7050 to 6900
- Move junction from TEKA-HARI-TELI-GENG from Chainage 21350 to 21151

- BURI-BHADRA has been shortened and now starts at first available cross-section at chainage 102 (was chainage 0)
- Cross-sections at TEKA-HARI-TELI-GENG at chainage 6800 and 7000 are identical. Chainage 7000 has been removed from the database
- Cross-sections at TEKA-HARI-TELI-GENG at chainage 42000 and 46800 are identical. Chainage 46800 has been removed from the database
- U-BHADRA has been shortened and now ends at last available cross-section at chainage 25000 (was 25600, where no cross-section is available)

With these changes the model runs smoothly with a time step of 5 min (or larger), which is significantly higher than the 1 min which is the limit in the curtailed model. The listed modifications/changes were implemented one by one and for each change the model was tested whether the modification had impact on the result.

The intention is to simulate the sedimentation taking place after TRM operation of Beel Kedaria was discontinued and the re-erosion when TRM operation of East Beel Khuksia has started. The cross-section survey best representing the situation after TRM operation of Beel Kedaria is the 2008 survey (c.f. Section 2.3), however this survey does not cover the full length of the river. The 2008 survey has therefore been used from chainage 0 to 39588 while the 2016 survey has been used from chainage 40800 to 47292 (ID IWM2008/16 in cross-sectional database). In Figure 3.3 the simulated water level in East Beel Khuksia using these data (black line) is compared with the corresponding result using the 2016 survey (blue line), only. There is a very significant difference in the simulated water levels. This suggests that it is of great importance to have cross-sectional survey data that are concurrent with actual simulation period.

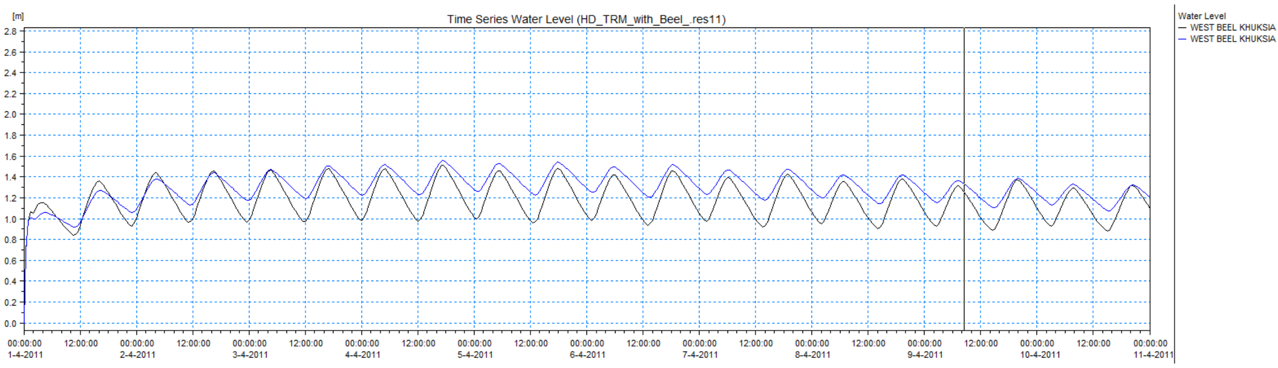

Figure 3.3 Simulated water level for two different sets of cross-sectional survey data.

3.3 Model Calibration

The hydrodynamic component of the SWRM is fully calibrated and verified hence there is no need to repeat this for the curtailed model. Boundary conditions are available for the period 4th January 2011 to 31st May 2012, only, whereas the actual simulation periods are January – April 2005 (Figure 2.1) and (say) February – May 2007 (Figure 2.3). Both of these periods will be represented by he simulation period 4th January to 4th April 2011. The "calibration" strategy will therefore be:

- To identify a simulated tide, where the tidal variation is similar with the observed tidal range (obtained through depth recordings, see Section 2.3).
- Compare observed and simulated sediment concentration for this particular tide and adjust model parameters until a satisfactory agreement with the observed sediment concentration has been achieved.

The model will subsequently be "verified" through

- Comparison of simulated and observed sediment concentrations for the subsequent neap and spring tide as well as spring tide observations within East Beel Khuksia.
- Testing the ability to simulate sediment accumulation/siltation in the Hari River for the period after discontinuation of TRM operation at Beel Kedaria.
- Testing the ability to simulate sediment erosion in the Hari River and sedimentation in East Beel Khuksia following initiation of TRM operation.

The simulation results are presented in Figure 3.4 through 3.11 and give rise to the following observations:

- In Figure 3.4 the observed water level (assuming a bed elevation of -3.2 m PWD) is compared to the simulated water level. The agreement between observed and simulated water level is very good, but this would also have been the case for numerous other tides in the selected simulation period, hence the phase (in the spring-neap-spring cycle is not well-determined).
- Figure 3.5 shows observed and simulated sediment concentrations. Again, the agreement is good. The sediment parameters used are listed in Table 3.1.

Table 3.1 Sediment parameters applied for the MIKE 11 model.

Parameter	Value
Settling velocity	0.5 mm/s
Critical shear stress for deposition	0.2 Pa
Critical shear stress for erosion	0.2 Pa
Erosion coefficient	0.05 $g/m^2/s$
Dry density of bed sediment	1000 kg/m^3
Sediment concentration downstream at boundaries	5 g/l

All the applied values are quite similar to those used in other model studies in Bangladesh and elsewhere.

- Figure 3.6 shows the water level for a full spring-neap-spring cycle. The simulation shows that the low waters become lower during neap tide, whereas the observations do not show the same behaviour. A possible explanation is that the full impact of the TRM operation has not materialised when the measurements were made during May 2007. Figure 2.3 shows that erosion of the cross-sections has commenced but it's not fully developed, thus the higher bed elevation keeps the water level at low tide up. The second spring tide is under-simulated by the model.

  These discrepancies between observations and model prediction suggest that a better agreement would be achieved by 1) re-run the model with proper boundary conditions and 2) by including morphological feedback in the simulations.

- Figure 3.7 shows simulated and observed sediment concentration in Hari River. The neap tide concentrations are well represented by the model, whereas the second spring tide concentrations are too small in the simulations. This corresponds well with the under-simulation of the tidal range (Figure 3.6). This underscores that the sediment concentration is very sensitive to the tidal range.

- Figure 3.8 and the zoom plot in Figure 3.10 show simulated water level in East Bell Khuksia at two adjacent locations. The tidal range is well predicted while the phase is 2-3 hours off. The phase of the tide in Hari River is well-predicted. Considering the proximity of the Hari River and the two locations within East Beel Khuksia, it is difficult to find a physical explanation for the apparent phase lag. The most likely explanation is therefore that the measurements must have been carried out at a different date or time or at a different location than stated in the data files.

- Figure 3.9 and the zoom plot in Figure 3.11 show simulated and observed sediment concentration in East Beel Khuksia at two the adjacent locations. The figures give rise to the following remarks:

    - The observed concentration is significantly higher than the simulated. In the 1D model setup the drainage canal(s) in the polders and polder surface have been lumped into one cross-section, where simulated flow velocity will be much smaller than in the drainage canals. This means that sediment will deposit quickly inside the polders in the model. In reality the flood flow will carry sediment further into the polders via the drainage canals and deposition first take place when the water spills into the polder. This discrepancy thus suggests that a 2D description is required to represent correctly the conditions within the polders.

    - In the simulation, the ebb flow (the water flowing out from the polder) does not contain any sediment (thus all sediment entering the polder will deposit). The observations do not confirm this at both stations. In fact, some of the highest observed concentrations at Chainage 4485 (red dots) are found during ebb flow. At Chainage 3979 the variation pattern is similar to the simulations except for one outlier. The sediment samples are collected very close to the bed (10-15 cm) especially those around low water, hence it may be that the sampler itself has stirred up sediment from the bottom. Another contributing explanation could be that part of the finer sediment fractions will remain in suspension inside the polder because of the low settling velocity. This could thus advocate for a multi-fraction modelling approach.

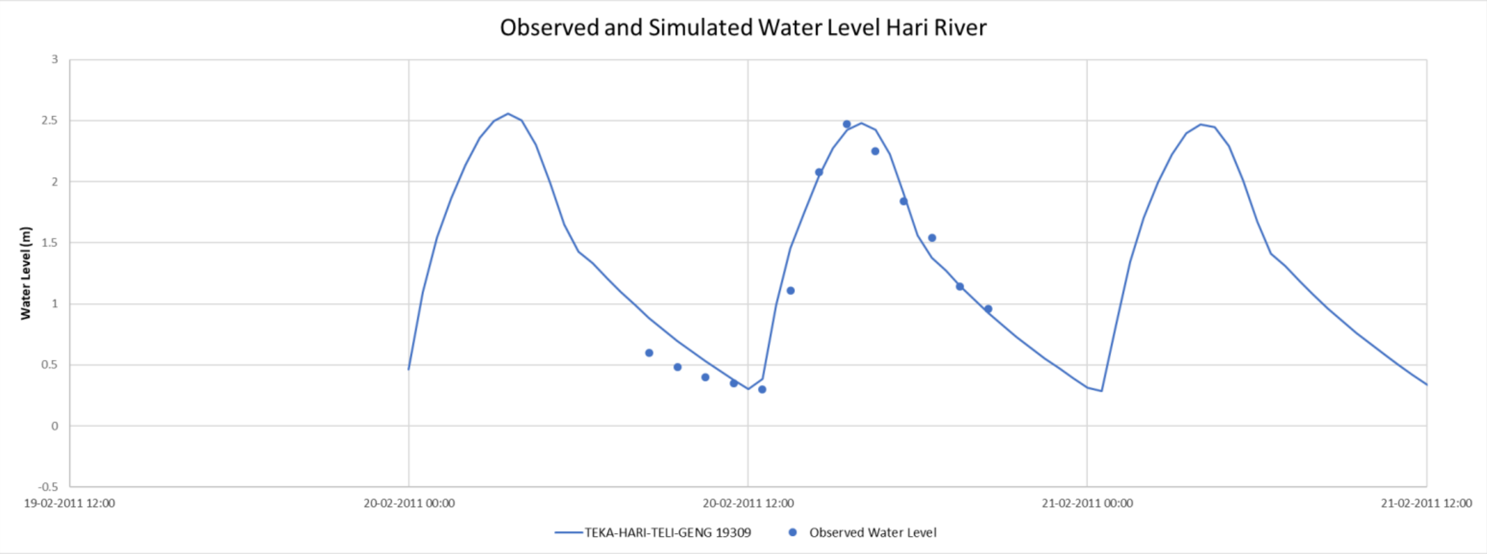

Figure 3.4 Simulated water level in Hari River compared to measured water depth assuming a bed elevation of -3.2 m PWD.

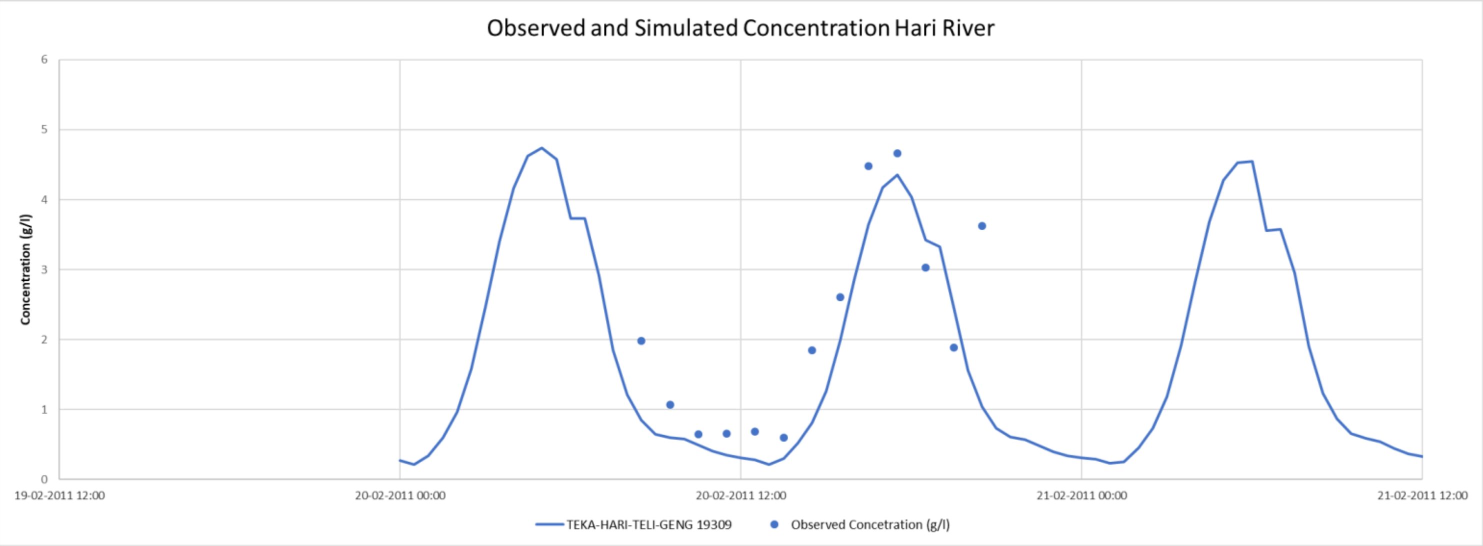

Figure 3.5 Simulated and observed sediment concentration in Hari River – calibrated sediment parameters.

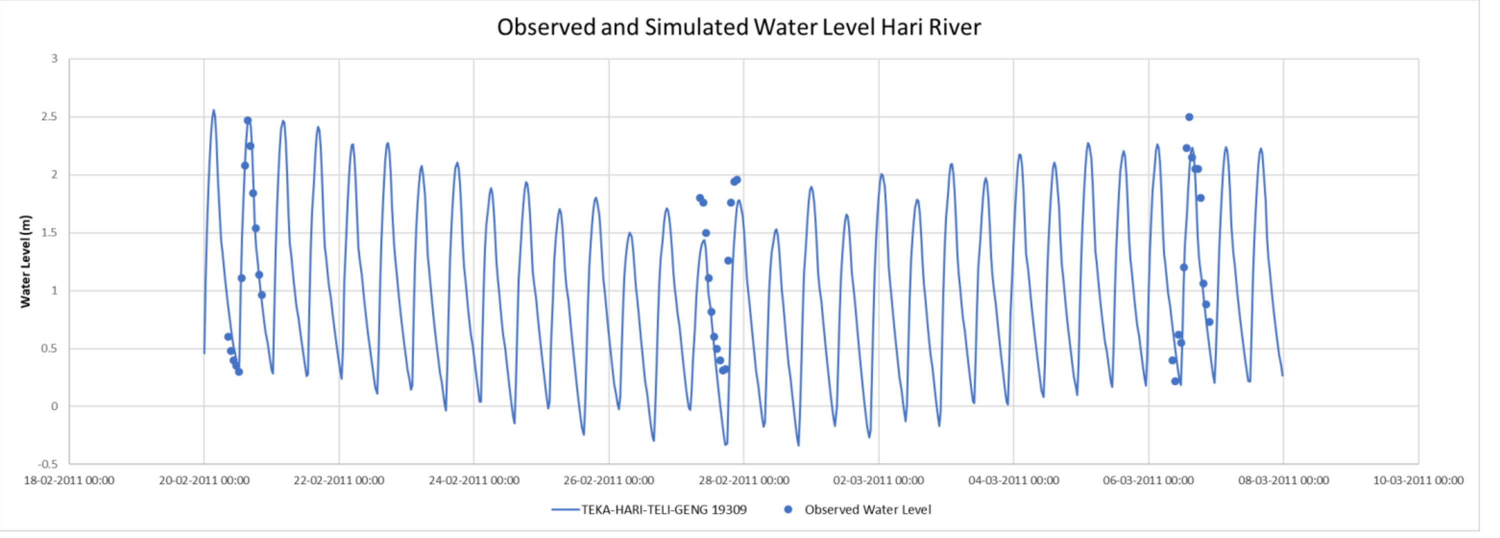

Figure 3.6 Simulated water level in Hari River compared to measured water depth assuming a bed elevation of -3.2 m PWD.

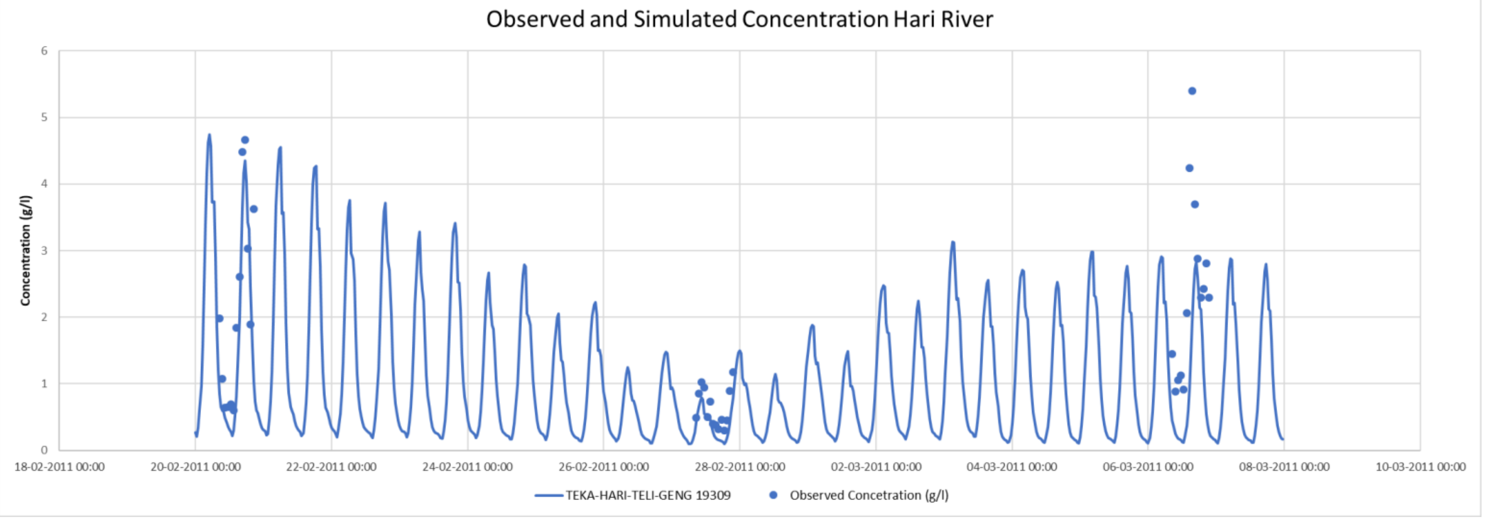

Figure 3.7 Simulated and observed sediment concentration Hari River – calibrated sediment parameters.

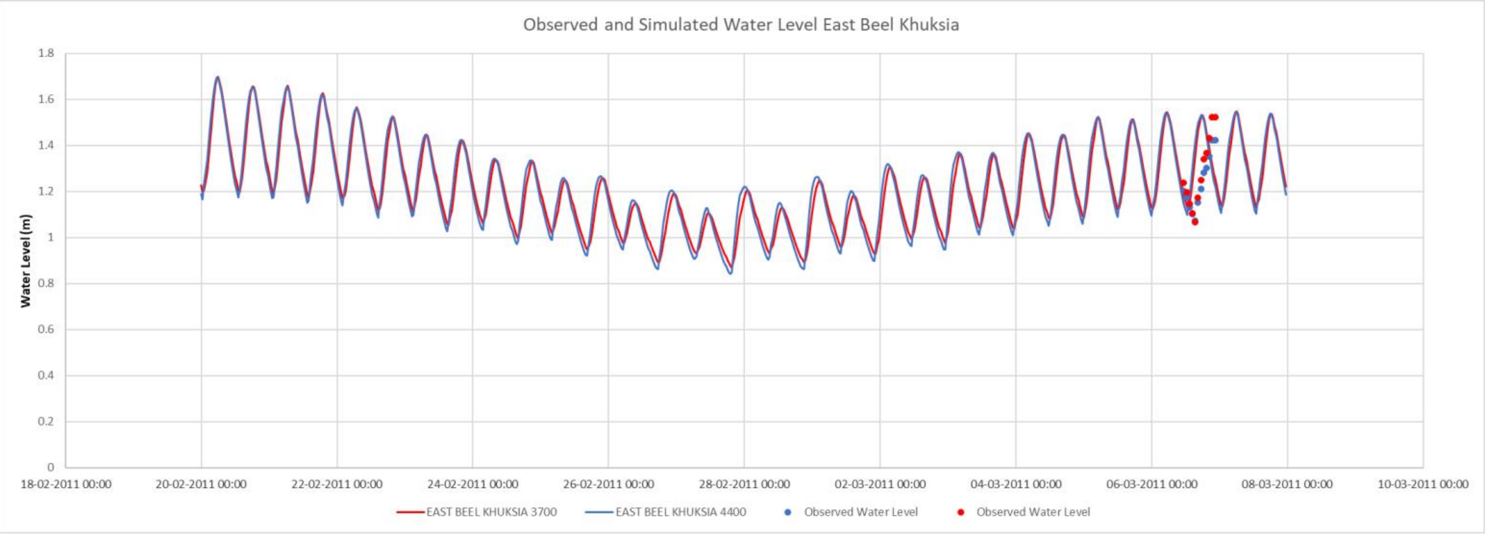

Figure 3.8 Simulated water level in East Bell Khuksia compared to measured water depth assuming a bed elevation of 0.6 m PWD.

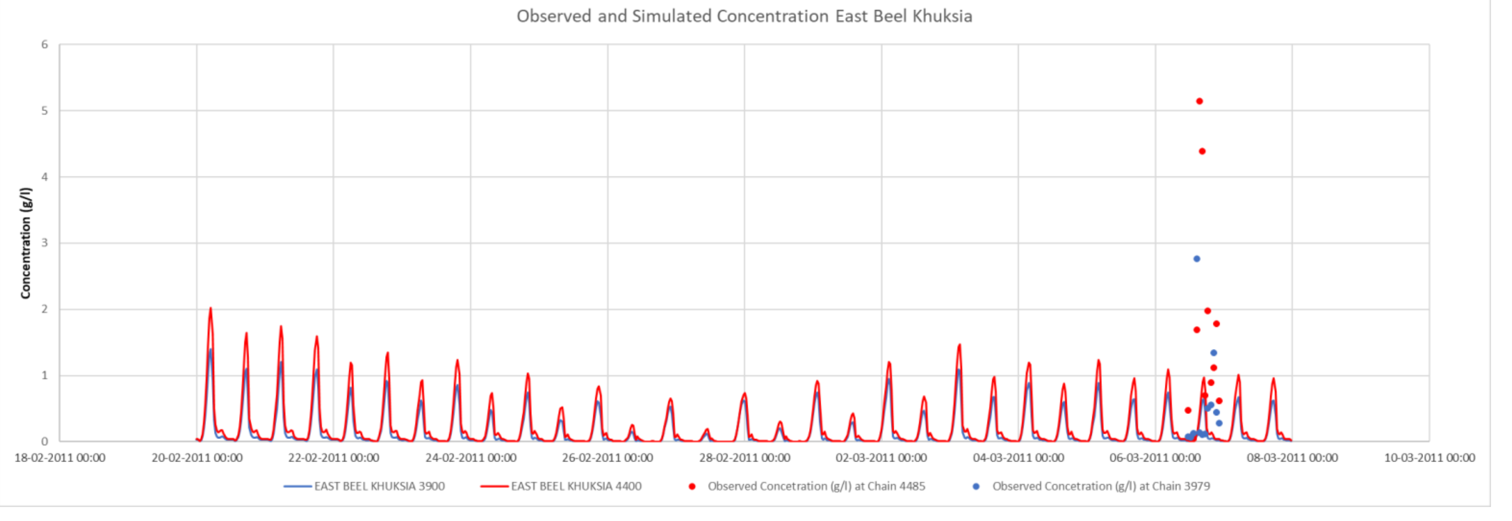

Figure 3.9 Simulated and observed sediment concentration East Beel Khuksia – calibrated sediment parameters.

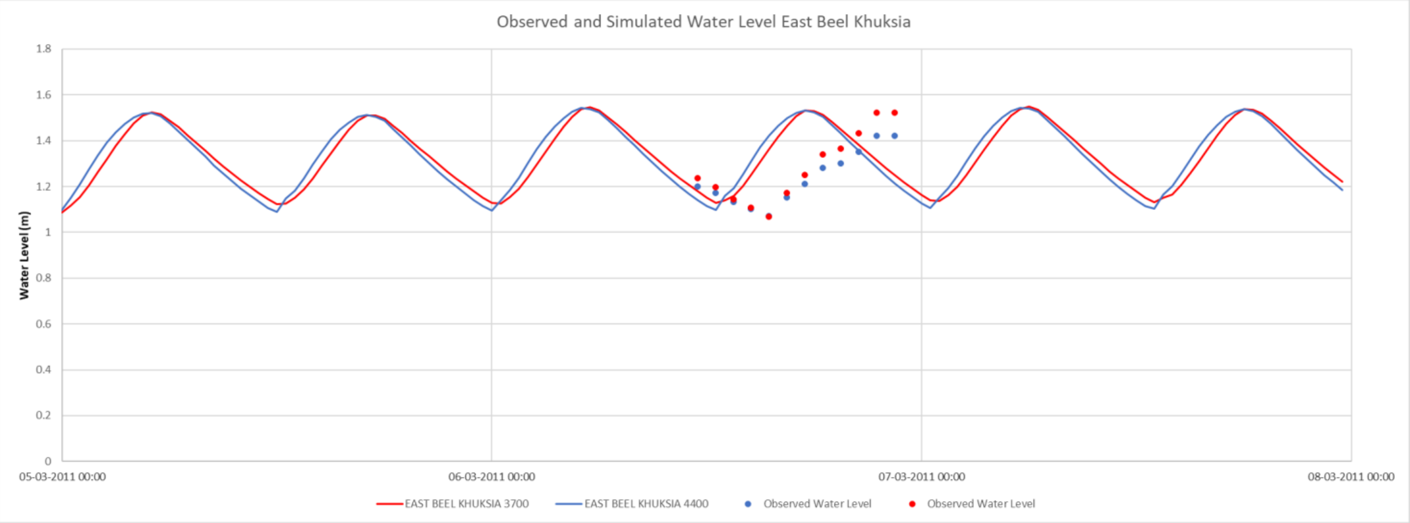

Figure 3.10 Simulated water level in East Bell Khuksia compared to measured water depth assuming a bed elevation of 0.6 PWD.

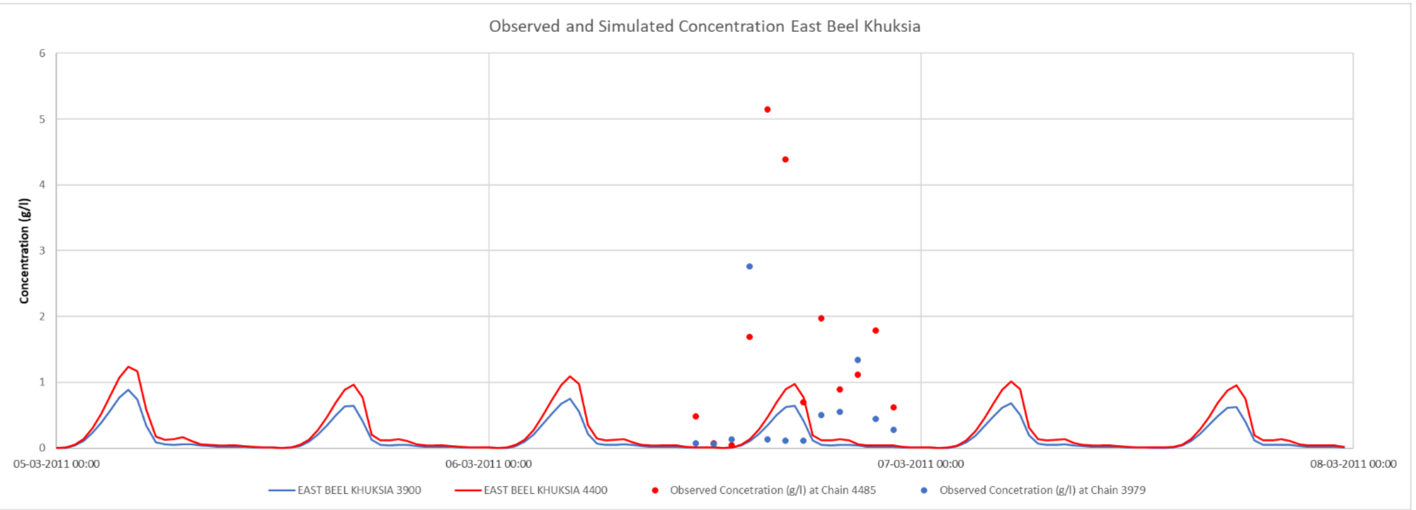

Figure 3.11 Simulated and observed sediment concentration East Beel Khuksia – calibrated sediment parameters.

3.4 Erosion and Deposition Before and During TRM Operation

In this section simulation results representing the erosion and deposition taking place before and during TRM operation at East Beel Khuksia are represented. The simulations are split into two steps:

- Step One: The situation immediately after TRM operation of Beel Kedaria was discontinued. Initial conditions are represented by no sediment at the riverbed and (the large) 2008 cross-sections. East Beel Khuksia is not included in the model setup. The period simulated is three months from 4/1 2011 to 4/4 2011 representing the period January – April 2005 (see Figure 2.1).

- Step Two: The situation after TRM operation of East Beel Khuksia has commenced. Initial condition is the simulated sediment accumulation at the bed in Step One and again the large 2008 cross-sections (the simulation is not (yet) morphological). The period simulated is again the three months from 4/1 2011 to 4/4 2011 but now representing three months during TRM operation (commencing Nov 2006).

However, initially the effect of the East Beel Khusksia on the tidal flow is explored. Figures 3.13 and 3.14 show the simulation result where the Hari river joins the Upper Bhadra River. In Figure 3.14 the tidal volume has been calculated. Without East Beel Khuksia the tidal volume is up to 3.5 mill m3 while East Beel Khuksia adds another 1.5 mill m3 to this. The tidal volume increases thus with about 40%. A similar increase of velocities may be expected while bed shear stresses may increase with about 100%. This is at the junction with the Upper Bhadra River. Further upstream closer to the link channel to East Bell Khuksia the relative impact of East Beel Khuksia will be bigger.

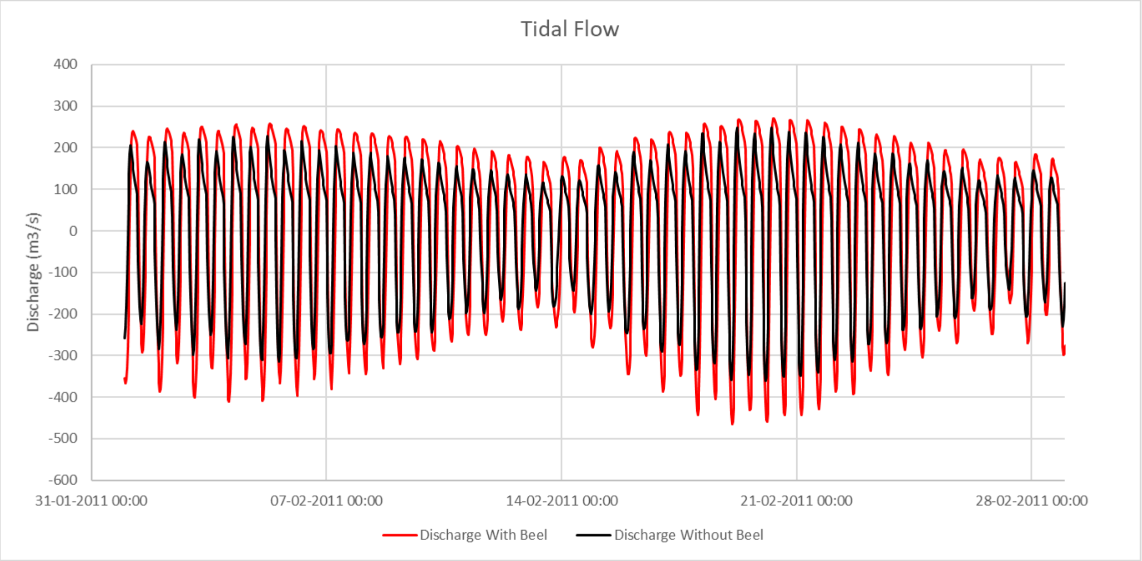

Figure 3.12 Simulated tidal flow with and without East Beel Khuksia included.

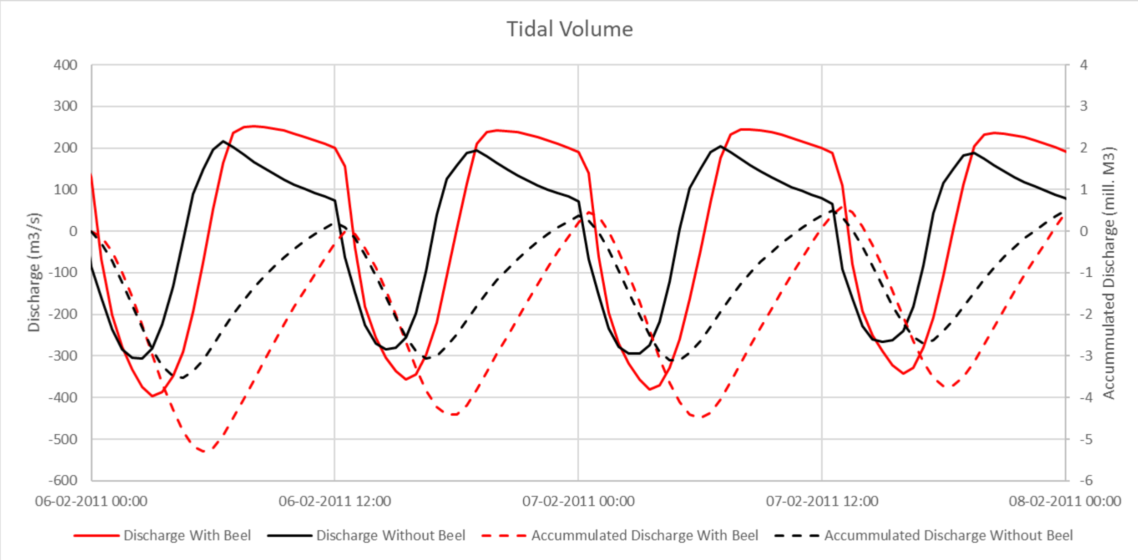

Figure 3.13 Simulated tidal flow and tidal volume with and without East Beel Khuksia included. This is a zoom of Figure 3.12.

In Figure 3.14 the simulated sediment dynamics is shown for the situation after TRM operation at Beel Kedaria has ceased and before TRM operation at East Beel Khuksia commences. The figure shows the strong asymmetry in sediment transport leading to a significant net transport of some 400,000 tons into the Hari River. This should be compared with the net accumulation of 800,000 tons estimated from observed cross-sections for a similar period (see Figure 2.1). The majority of the sediment is accumulated in the lower part of the Hari River (downstream the location of the link channel into East Bel Khuksia.

Figure 3.14 presents the simulated sediment dynamics when East Beel Khuksia is under TRM operation. It is noticed that both the transport during ebb and flood flow has increased due to the increased tidal volume (compared to the simulation presented in Figure 3.14), but surprisingly the net transport is nearly unchanged. It is noticed that only part of the deposited sediment re-erode (viz about 200,000 tons). A closer inspection of the simulation result indicates that the deposited sediment in the lower part of the Hari river does not re-erode. Nearly all of the sediment eroded from the riverbed plus the net sediment transport into Hari River ends up in the East Beel Khuksia, where close to 600,000 tons deposit. For a period of four months, we have calculated the deposited volume to 1.2 mill m^3 (an uncertain estimate, see Section 2.3). Assuming a density of 1 tons/m^3 this corresponds to 1.2 mill tons, thus twice the simulated deposition.

Considering all uncertainties (e.g. regarding boundary and initial conditions), the very simplistic model approach, few data used for model calibration etc. the agreement between observations and simulation results are remarkably good.

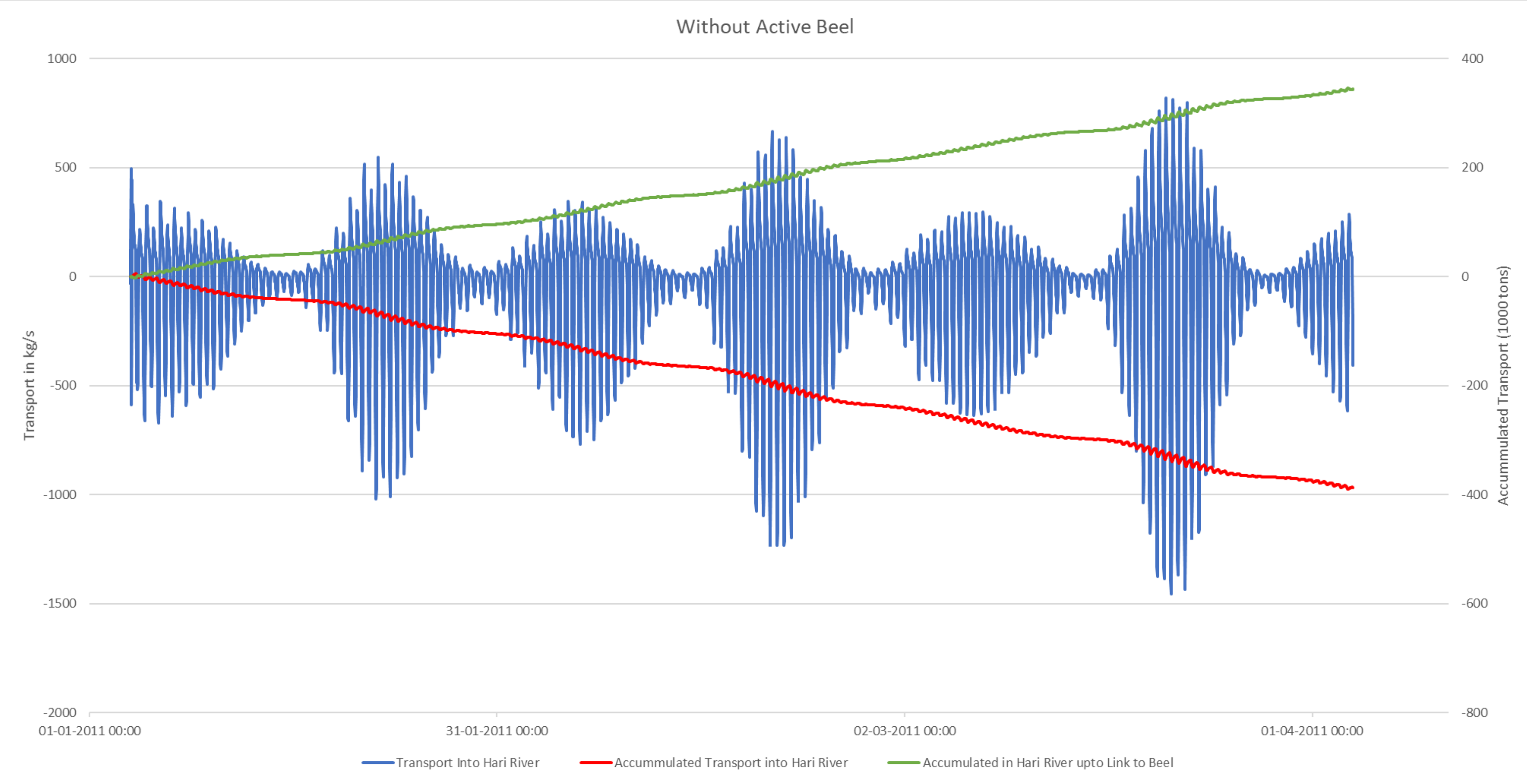

Figure 3.14 Simulated sediment dynamics when East Beel Khuksia is not included. The Blue line is the simulated sediment transport (kg/s) in Hari River at the Junction with Upper Bhadra. The Red line is the accumulated transport (1000 tons) at the same location while the Green line is the accumulation of sediment at the riverbed between the junction and the link channel into East Beel Khuksia.

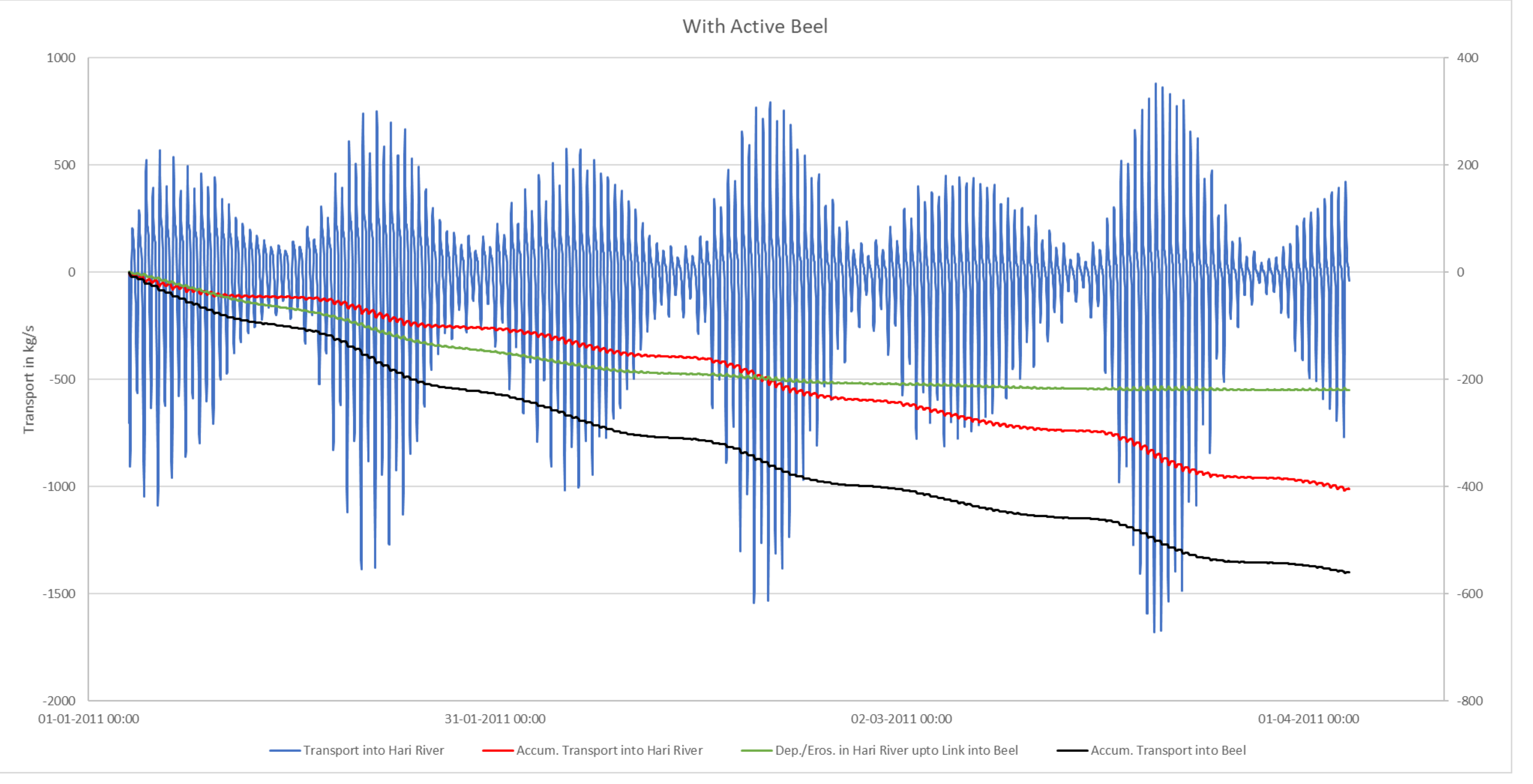

Figure 3.14 Simulated sediment dynamics when East Beel Khuksia is under TRM operation. The Blue line is the simulated sediment transport (kg/s) in Hari River at the Junction with Upper Bhadra. Negative value is transport during flood flows. The Red line is the accumulated transport (1000 tons) at the same location while the Green line is the accumulation of sediment at the riverbed (negative value means erosion/depletion of sediment) between the junction and the link channel into East Beel Khuksia and the Black line represents the simulated deposition (1000 tons) in the East Beel Khuksia.

4 Model Development (MIKE 21)

4.1 Introduction

Based on boundary conditions derived from the MIKE 11 model a more detailed 2D model (MIKE21 FM) has been developed using the historical topography inside the Polder 24 and 135 cross sections surveyed in 2015 and covering the reach from the Bhabodaho regulator and down to Ranai. The polder bathymetry of East Beel Khuksia is based on topographic survey of the polder from February 2007.

4.2 Construction of Model Mesh and Bathymetry

The distance between the 135 surveyed cross sections is in general too large to ensure a correct description of the thalweg and channel geometry of the Hari River, when generating a flexible mesh and bathymetry using the build-in standard interpolation technique of the mesh generator software tool. When the thalweg is shifting from one bank to the other there is a risk for generation of artificial bars that creates a none-physical flow resistance and in some cases even block for the tidal flow. To avoid this phenomenon a technique to improve the bathymetry basis has been developed taking advantage of the MIKE 21 C curvilinear grid generator tool, which has an option that allows interpolation aligned with the streamwise direction of a curvilinear grid. This technique makes it possible to create additional cross sections and ensure a proper bathymetry interpolation. A comparison of the two methods is illustrated in Figure 4.1 and Figure 4.2. It is seen that the streamwise interpolation or the creation of additional cross section data is required to get a proper channel bathymetry. The technique is applied for the entire reach of the Hari-Teka River in order to develop a suitable bathymetry for the TRM model. Also, the channels routing the tidal flow inside the TRM needs to be resolved to ensure that the model can transport and carry the suspended sediment being brought into the TRM further inside.

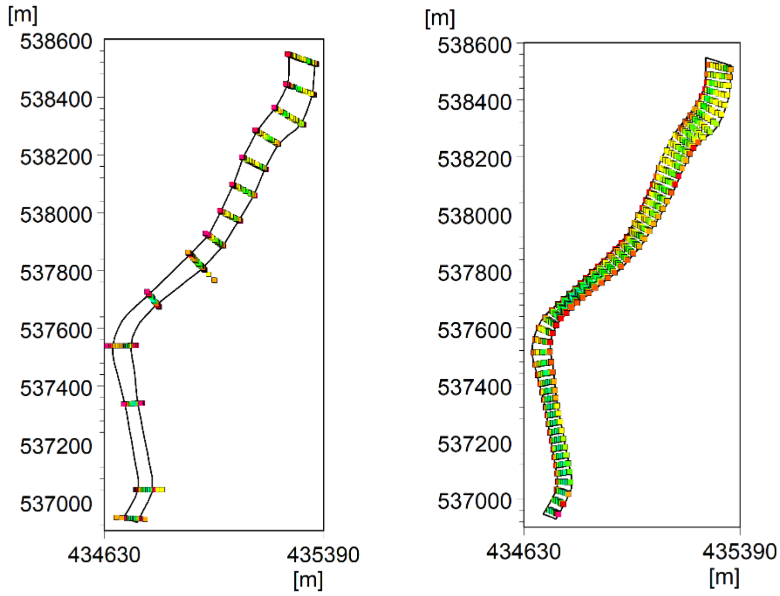

Figure 4.1 Left: The original 14 measured cross sections. Right: Cross section information obtained using streamwise interpolation resulting in a total of 59 cross sections

Figure 4.2 Left: Interpolated bathymetry based on the 14 measured cross sections. Right: Interpolated bathymetry based on the 59 created cross sections.

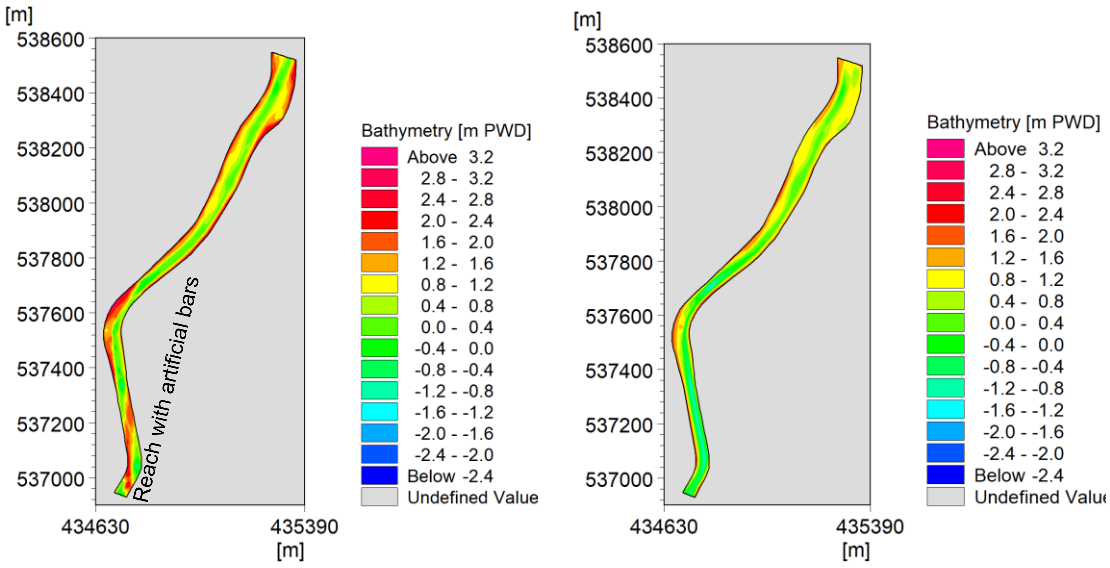

Figure 4.2 Left: Interpolated bathymetry based on the 14 measured cross sections. Right: Interpolated bathymetry based on the 59 created cross sections.

Applying this technique to improve the bathymetric basis a model mesh and bathymetry for the Hari River was established. The model mesh and bathymetry are shown in Figure 4.4. The micro-scale model is constructed so that it covers the reach from the Bhabodaho regulator in the north to Ranai in the south.

The Hari River model was extended into a TRM model that includes the East Beel Khuksia. The basis for that was a topographic survey of the polder from February 2007. The intensity of the survey was too low to generate a proper bathymetry of the polder and resolve the drainage channel network inside the polder. To accommodate for that aerial photos were used in combination with the polder surveys from February 2007 and May 2007 to identify the channel network inside the polder and estimate the bed levels. By separating the channels and flood plains additional bathymetric data was constructed to differentiate between the two types of areas and to establish a proper basis for generation of the polder bathymetry. Figure 4.3 shows an example of the established bathymetric basis. The channel network inside the polder can clearly be identified and likewise the floodplains.

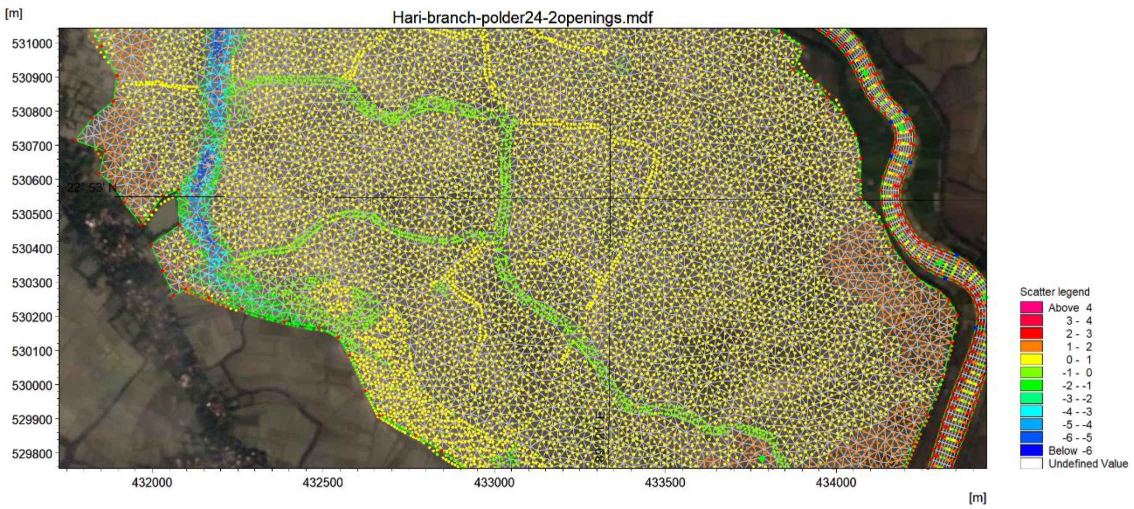

Figure 4.3 Map showing an example of the established bathymetric basis inside the polder and the peripheral river.

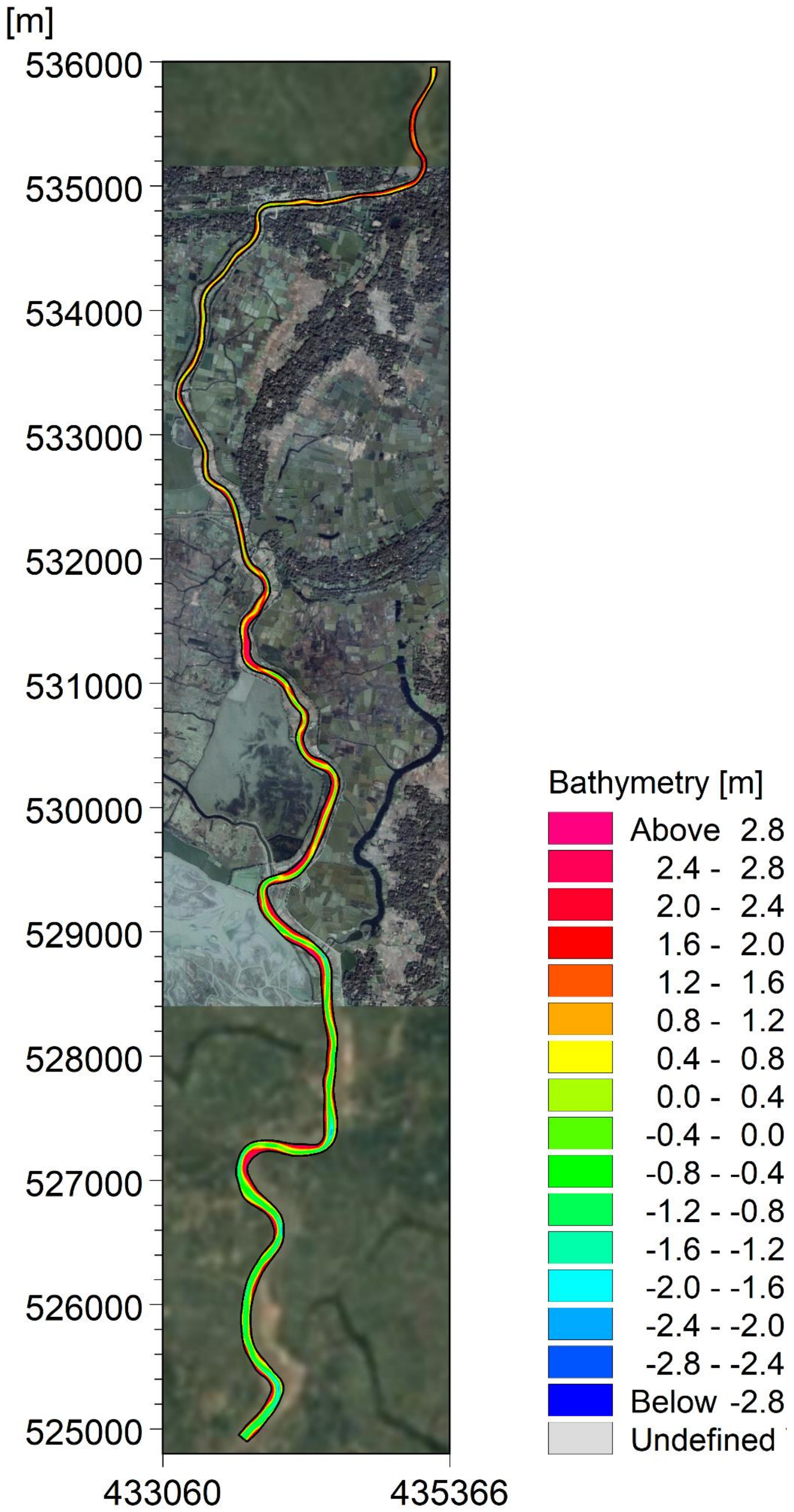

Figure 4.4 Bathymetry of the Hari River model.

The TRM model mesh and bathymetry are constructed with two openings. One in the southern end and one on the eastern side of the polder. By applying the structure module in MIKE 21FM and specifying a closed gate structure at the entrance channel the model mesh and bathymetry can be used to investigate TRM with one opening either to the south or to the east. The TRM model and bathymetry is shown in Figure 4.5.

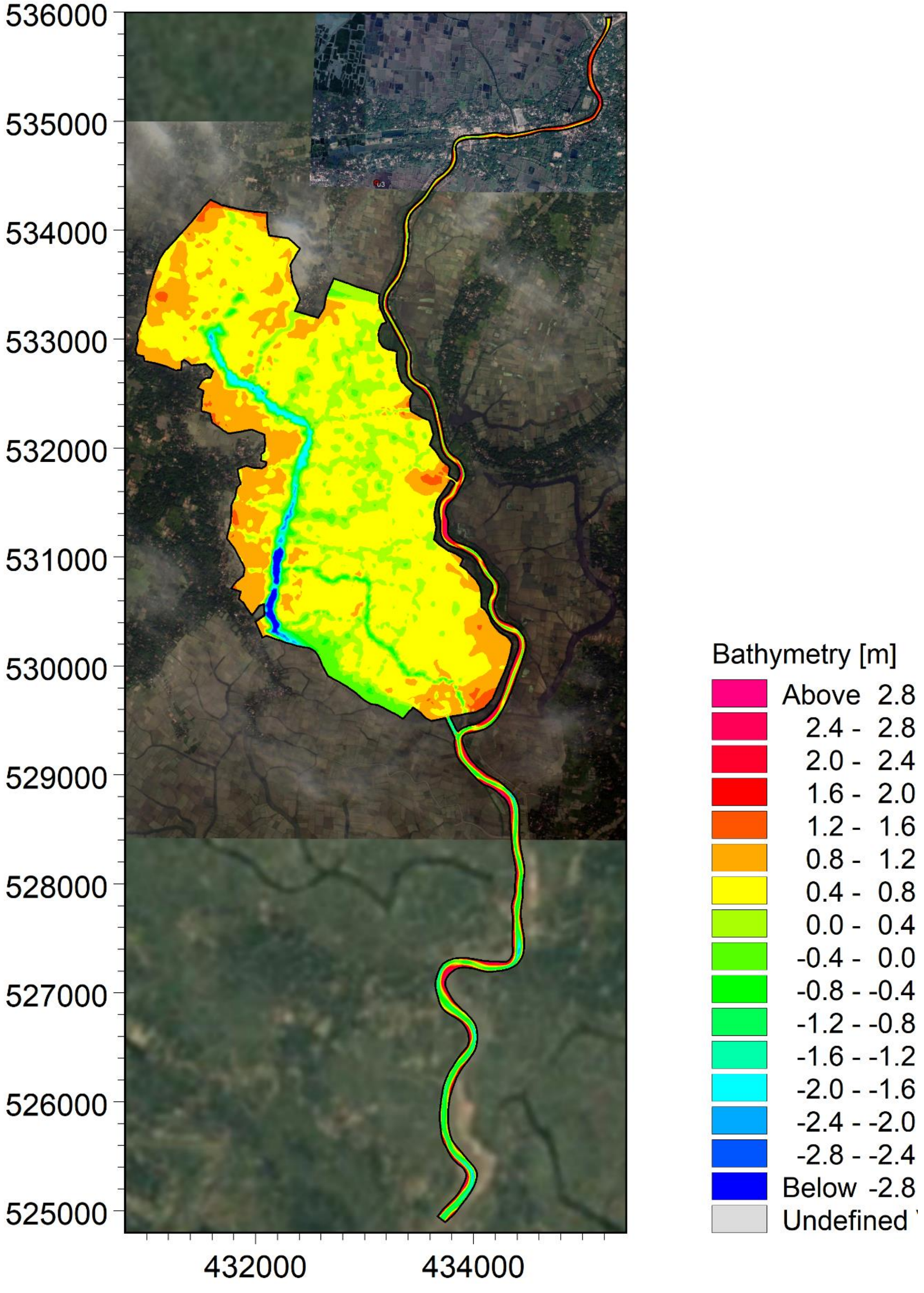

Figure 4.5 Bathymetry of the Hari River and East Beel Khuksia model.

4.3 Hydrodynamic Boundary Conditions

The boundary conditions for the model must be chosen, so that they only will be affected in a minor degree due to the activation of TRM. An opening into the polder will increase the tidal prism significantly and thereby also change the tidal discharge at the downstream boundary. The tidal elevation, however, will not be significantly affected and the model setups are therefore established with a water level time series from the MIKE 11 model extracted at Ranai. The upstream boundary is located at the Bhabodaho regulator. For the upstream boundary condition, it is therefore chosen to use a discharge time series from the MIKE 11 model extracted at the Bhabodaho regulator. The extracted time series was modified, so that the specified discharge represents the running average of 6 hours to avoid spurious fluctuations and uni-directional flow. The downstream water level boundary time series is shown in Figure 4.6 and the upstream discharge time series in Figure 4.7.

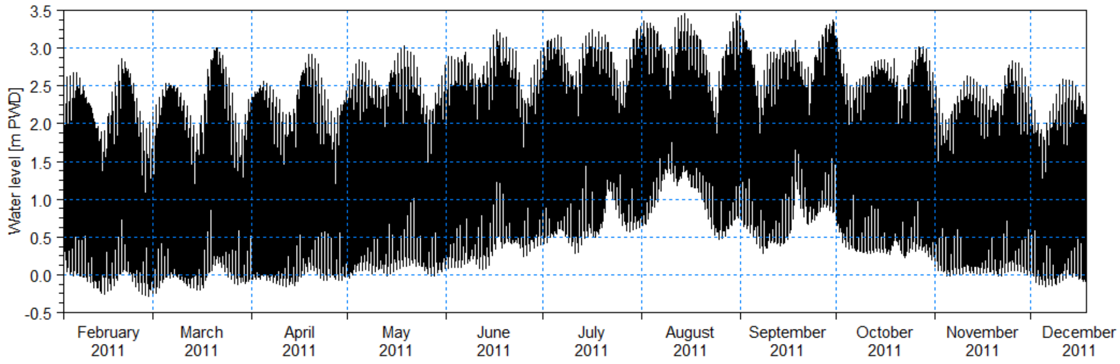

Figure 4.6 Water level time series applied for the downstream boundary condition.

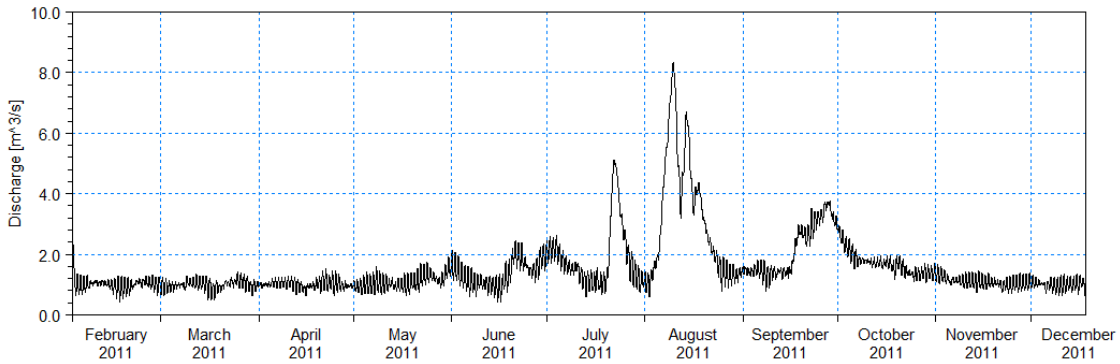

Figure 4.7 Discharge time series applied for the upstream boundary condition.

4.4 Measurements, Model Parameters and Calibration

The fact that the channel bathymetry of the Hari River is based on surveyed cross sections from 2015, the polder bathymetry from 2007 before activation of TRM, and the modelling period covers 2011 conditions makes it impossible to make a meaningful model calibration against observations. Water levels and discharge measurements from 2011-12 are available, but at this point in time the TRM operation has be ongoing for 4-5 years and thereby not comparable. Water levels were observed at six gauging stations during the period August 2011 to April 2012. The location of the gauging stations is indicated in Figure 4.8. Lebugati and Teka are located upstream the Polder 24 TRM basin, while Ranai is located downstream. Kagbandha and Katakhali are located inside the TRM basin. Kali Charanpur is inside Polder 24, but outside the TRM basin.

Figure 4.8 Water level gauging stations.

The water level data are based on manually recorded readings. For some periods water levels are recorded hourly, while for other periods every 3 hour. No recordings were made during the night. Examples of the water level recordings are shown in Figure 4.9 and Figure 4.10.

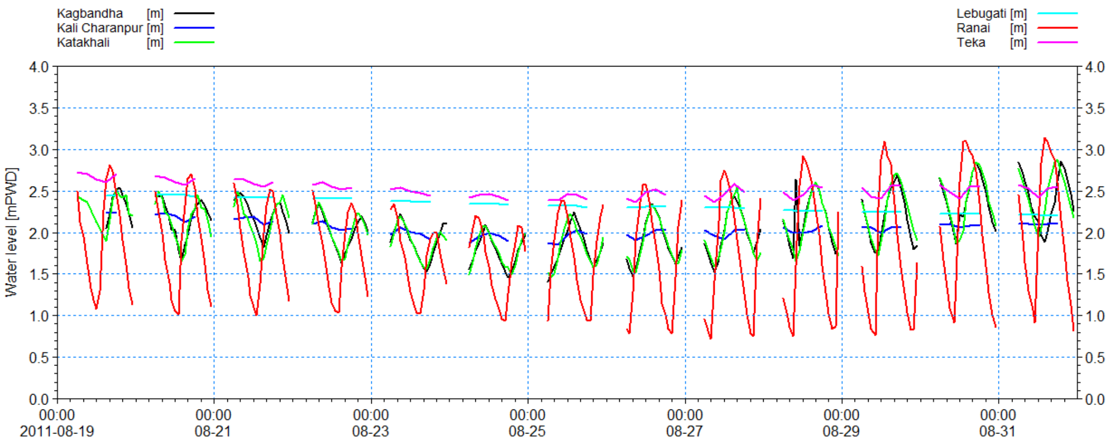

Figure 4.9 Observed water levels at the six gauging stations in August 2011.

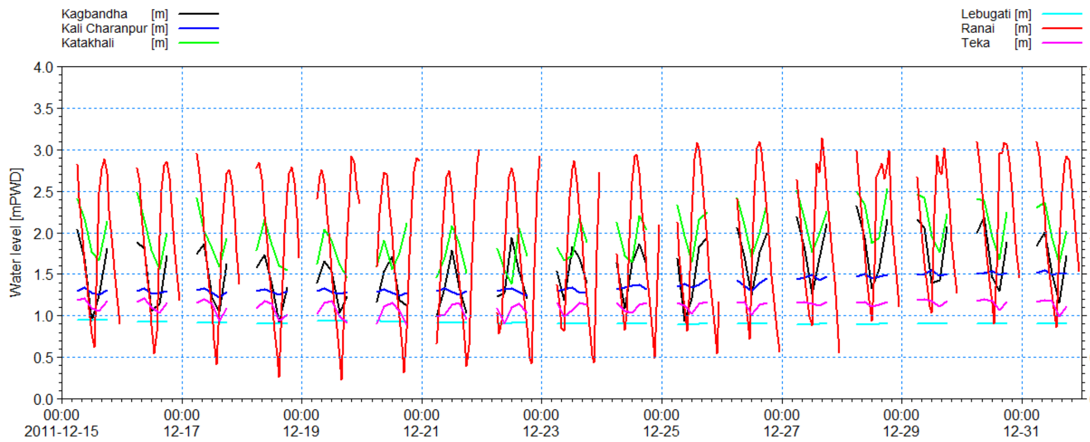

Figure 4.10 Observed water levels at the six gauging stations in December 2011.

It is seen that the observed tidal range at Ranai are in reasonable accordance with the time series shown in Figure 4.6.

Two survey campaigns of the tidal discharge were carried out at Ranai downstream the TRM basin for a tidal cycle on the 9th September 2011 and the 14th September 2011.

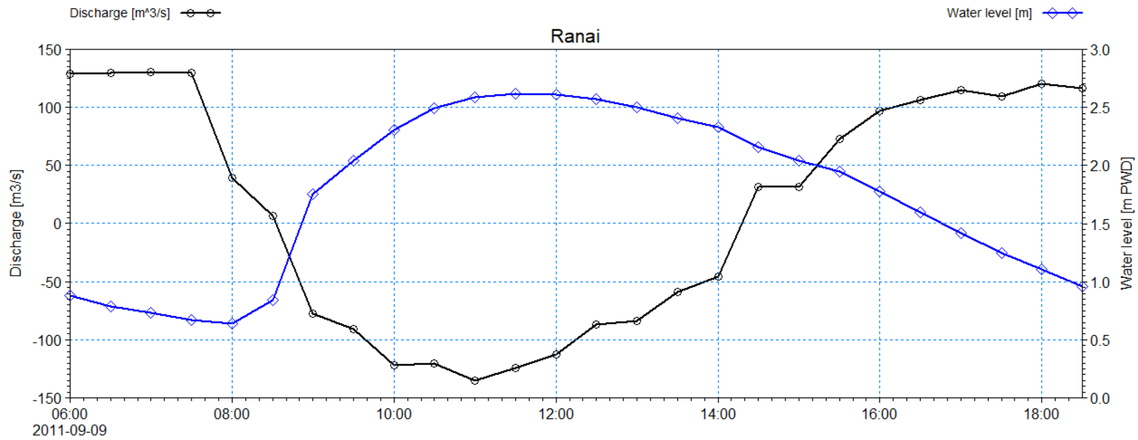

Figure 4.11 Discharge and water level observations at Ranai 9th September 2011.

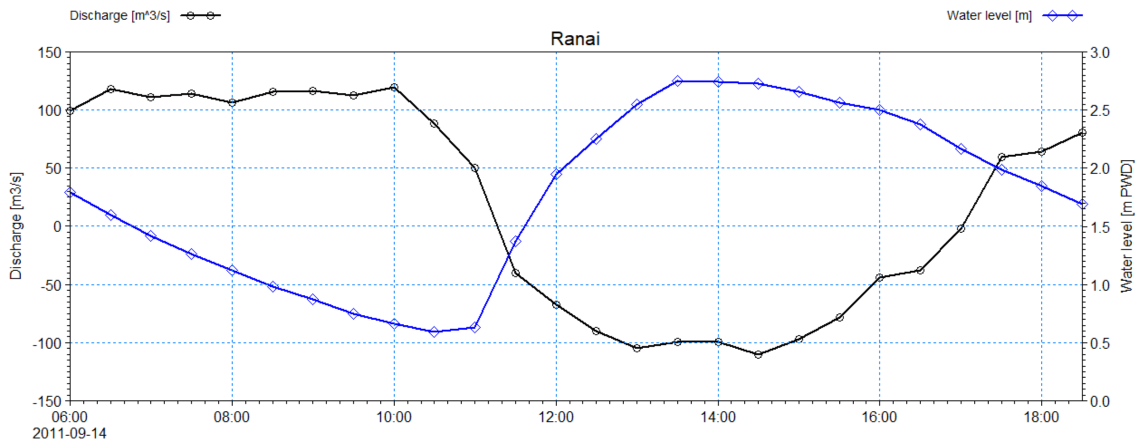

Figure 4.12 Discharge and water level observations at Ranai 14th September 2011.

The surveyed discharges are obtained at a point in time where the TRM has been operated for almost 4,5 years. The continuous deposition of sediment inside the polder reduces gradually the tidal prism over time. It is therefore expected that the tidal generated discharges are larger than the ones indicated in the plots during the first years of TRM operation.

The bed sediments are expected to primarily consist of silt. Samples of grain size distribution is only available at Bhadra located downstream of Ranai. The grain size distributions of the bed sediment in the middle of the channel and at the right bank are shown in Figure 4.13 and Figure 4.14. It is seen that the content of clay and sand is very low.

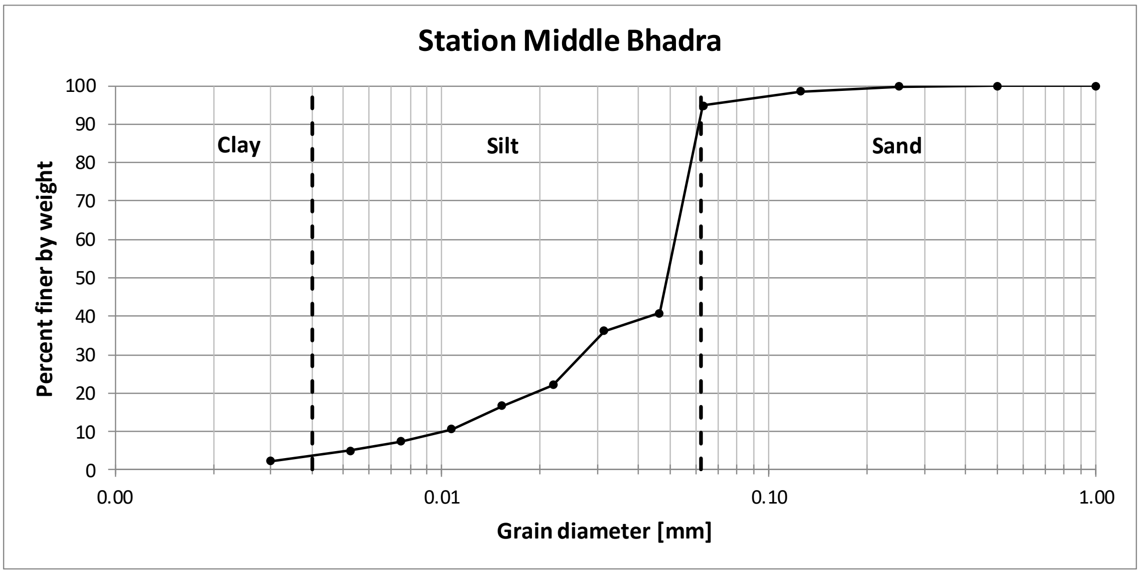

Figure 4.13 Grain size distribution of bed sediment in the central part of the channel at Bhadra.

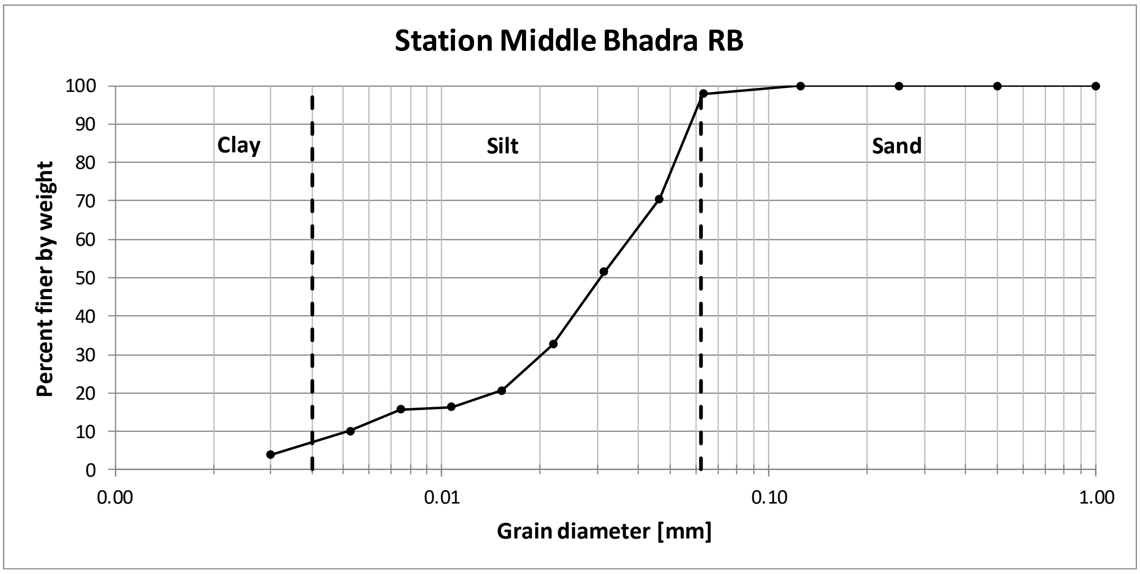

Figure 4.14 Grain size distribution of bed sediment at the right bank at Bhadra.

Suspended sediment samples have been collected at Ranai and near the channel entrance to the eastern side of the polder (Beel Khuksia) during campaigns in 2011 and 2012. The measured sediment concentrations at the two sites are shown in Figure 4.15 and Figure 4.16. From the plots, it is seen that there is a quite large temporal variation with tide and season.

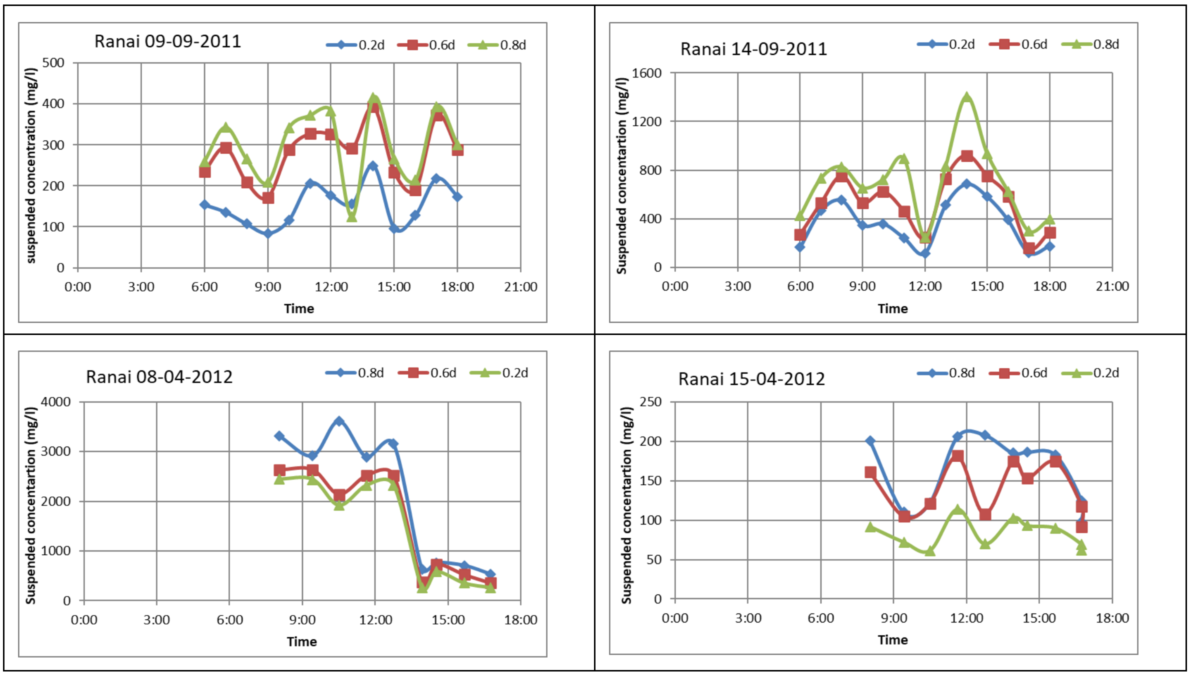

Figure 4.15 Observed suspended sediment concentrations at Ranai.

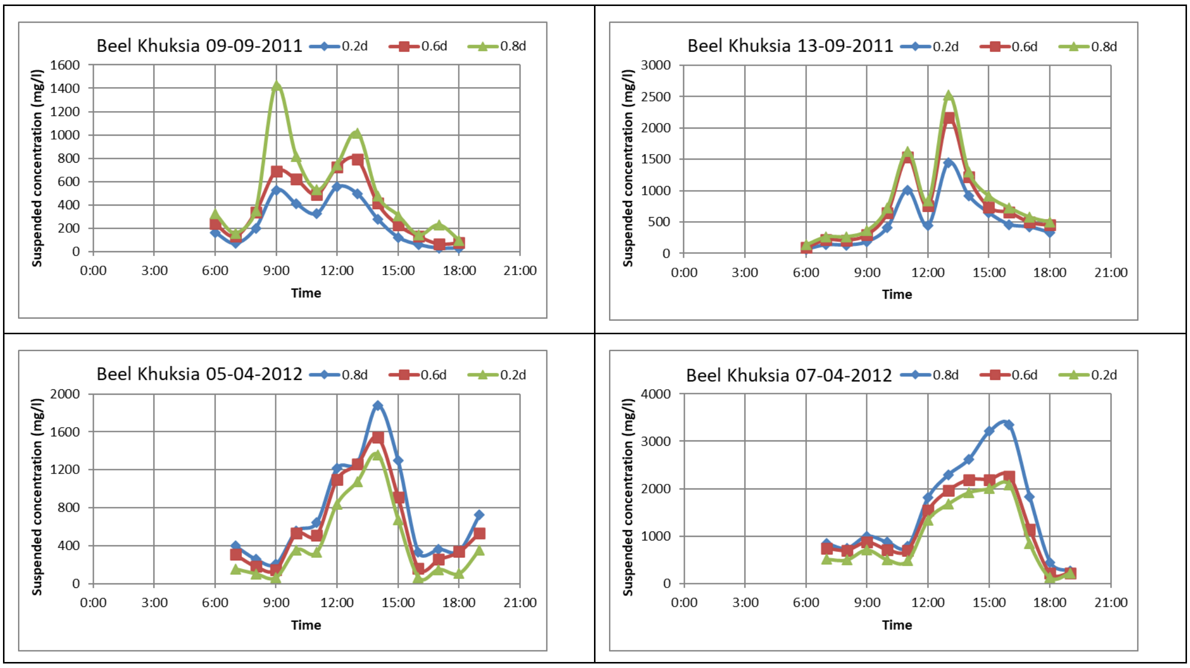

Figure 4.16 Observed suspended sediment concentrations at Beel Khuksia

The TRM model is mainly made as a conceptual model with the purpose of investigating the TRM concept and related dynamics. Table 4.1 contains a list of the model parameters applied for the modelling. The Manning number affects the flow resistance. If lowering the Manning number, the tidal induced discharge will also decrease corresponding to a damping of the dynamics. When specifying a larger settling velocity sediment will drop out of the water column faster, when increasing the critical shear stress for deposition one will allow deposition to take place in a longer time of the tidal cycle and if the critical shear stress is increased erosion will take place in a shorter time of the tidal cycle. The erosion coefficient is affecting the erosion rate and thereby how much sediment is being eroded during one tidal cycle. The dry density is determining the bed volume of the deposited sediment and the downstream sediment concentration will determine how much sediment that enters to the system with the tide. The suspended sediment boundary condition is only active during inflow. The behaviour of the TRM model will be quite sensitive to model parameters being specified, so it can be quite a challenge to find the right combination of parameters. Especially, because the morphological calculations are quite time-consuming, it is demanding to rerun the model calculations with a modified parameter combination.

Table 4.1 Applied MIKE 21 model parameters.

Parameter	Value
Manning number	65 $m^{1/3}/s$
Settling velocity	0.5 mm/s
Critical shear stress for deposition	0.2 Pa
Critical shear stress for erosion	0.2 Pa
Erosion coefficient	0.1 $g/m^2/s$
Dry density of bed sediment	1000 kg/m^3
Sediment concentration downstream with TRM	1.8 g/l
Sediment concentration downstream without TRM	0.4 g/l
Sediment concentration upstream	0.05 g/l

All the applied values are quite similar to those used in the MIKE 11 model and other model studies in Bangladesh and elsewhere.

4.5 Model Results

Three conceptual model scenarios have been examined and analysed with respect to tidal envelopes, morphological development and tendencies to erosion and siltation. The scenarios are as follows:

- Hari River without TRM
- Hari River and East Beel Khuksia with TRM and open entrance channel at the southern end
- Hari River and East Beel Khuksia with TRM and open entrance channel at the eastern side

Five cross sections as indicated on Figure 4.17 have been defined to keep track on how TRM and the morphological development of the system affect the tidal generated discharge. Furthermore, the predefined cross sections are used to evaluate the sediment budget of the investigated systems. Flow and sediment transport are only taking place through the Polder S and Polder E cross sections when the entrance has been specified as open.

The polder entrance channel is modelled as having an alluvial bed, i.e. the model is allowed to erode the initially predefined cross section and adapt to the capacity of the polder.

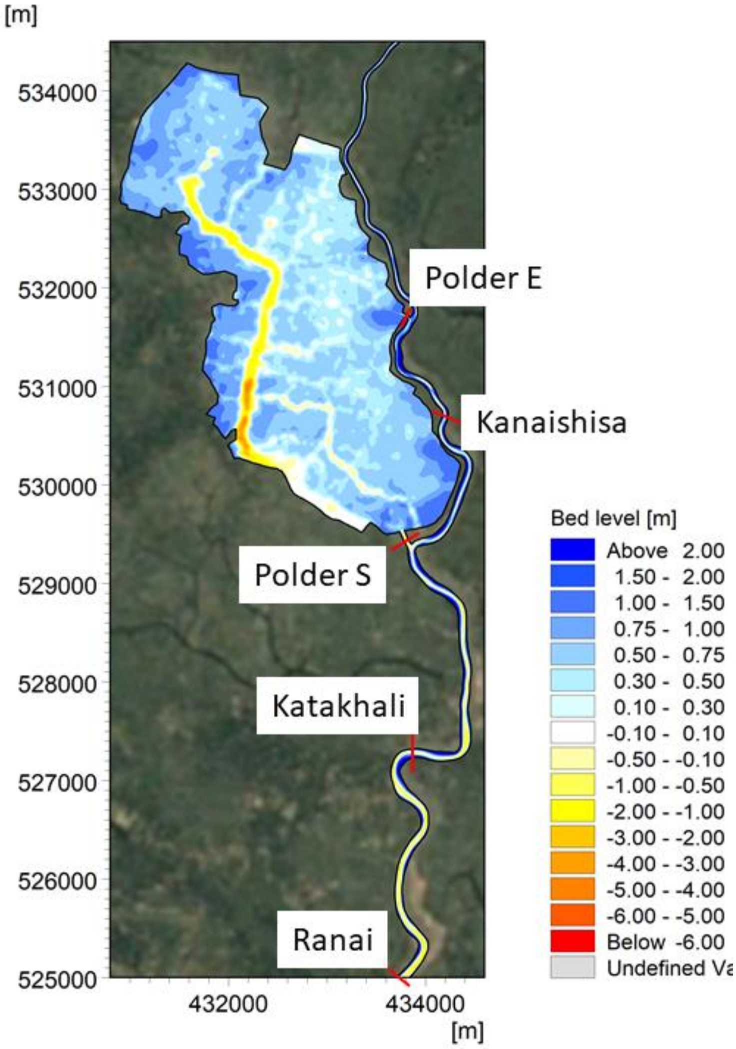

Figure 4.17 Location of cross sections used to analyse the development in tidal discharge and sediment transport.

4.5.1 The Hari River without TRM

The Hari River has a tendency to siltation due to the tidal assymetry, which creates an upstrem directed net sediment transport, which decreases with the tidal prism. First step has therefore been to model the Hari River and try to reproduce the tendency to siltation. For this model a lower value (0.4 g/l) is applied for the suspended sediment concentration at the downstream boundary compared to the TRM models (using 1,8 g/l), due to the much smaller tidal prism.

The morphological model is run cyclic six times, i.e. the modelling period covering almost a year is modelled repeatedly using the end bathymetry of the previous cycle. The modelling is thereby representing a period of almost six years.

For a siltating branch as the Hari River the tidal generated discharge will slightly decrease over time as a consequence of an increased flow resistance and the reduction of the tidal prism. The modelled flow discharges at Ranai, Katakhali and Kanaishisa are plotted in Figure 4.18 to Figure 4.20 for all six cycles. The plots show how the tidal discharge decreases when moving upstream due to the smaller tidal prism and how siltation of the Hari branch over the morphological cycles gradually reduces the tidal generated amplitudes.

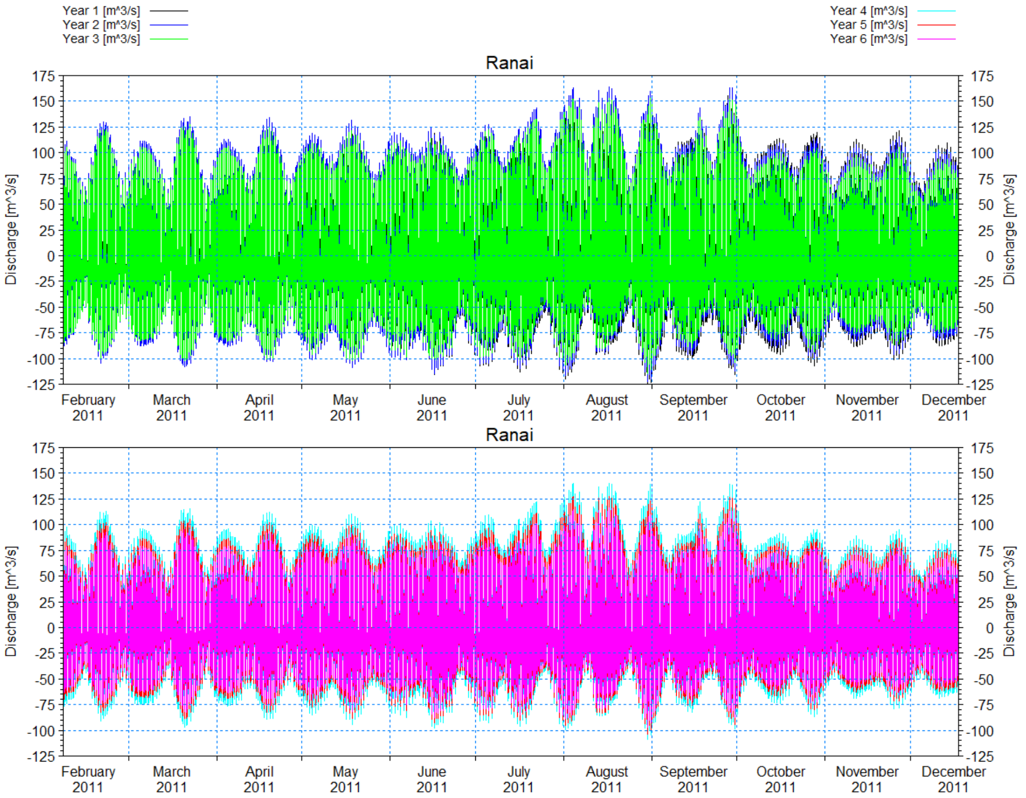

Figure 4.18 Modelled tidal generated flow discharge at Ranai for Year 1-3 (top) and Year 4-6 (bottom) without TRM. Discharge is defined positive for upstream directed flow.

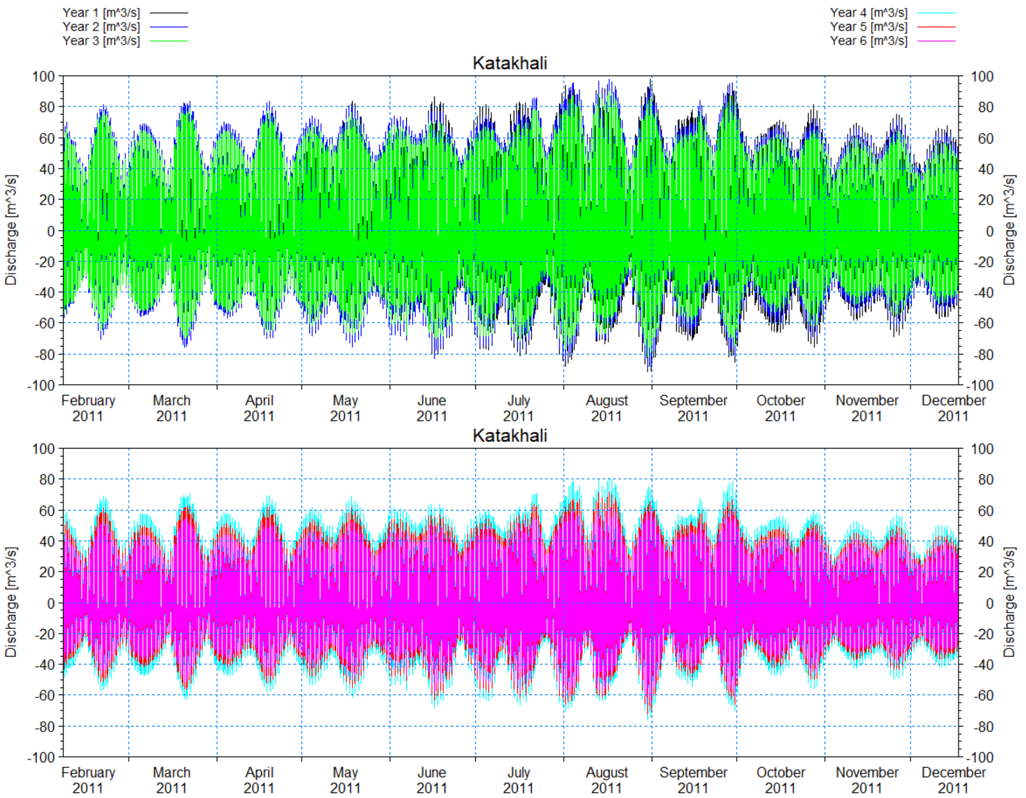

Figure 4.19 Modelled tidal generated flow discharge at Katakhali for Year 1-3 (top) and Year 4-6 (bottom) without TRM. Discharge is defined positive for upstream directed flow.

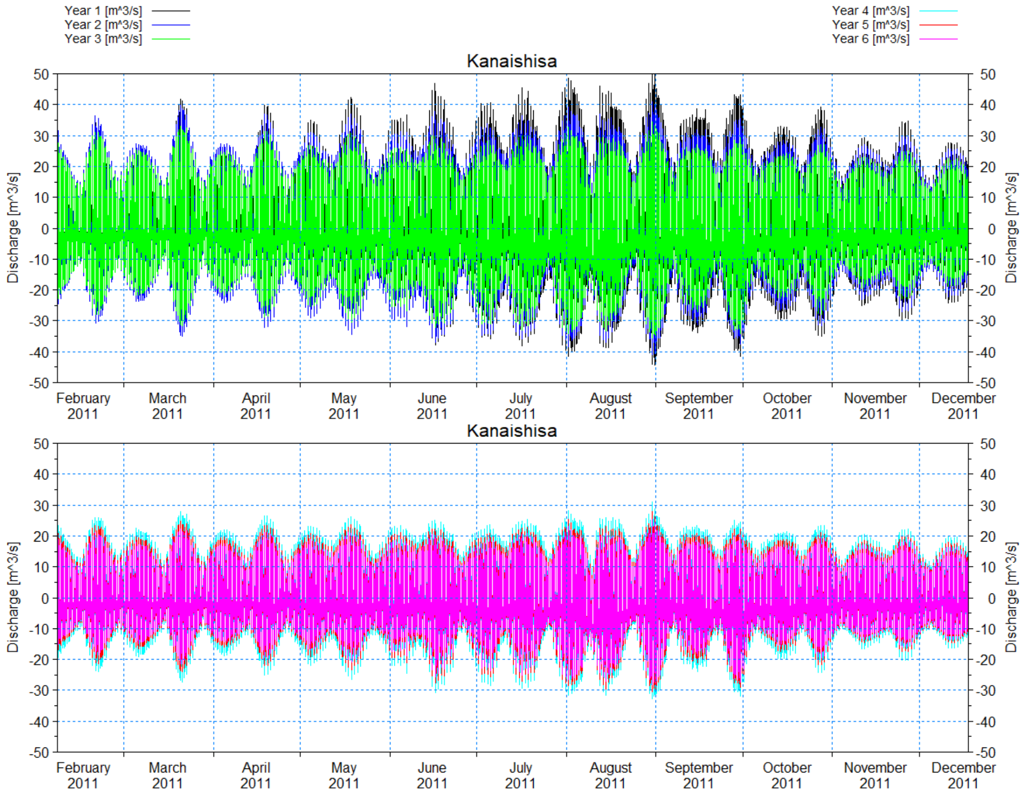

Figure 4.20 Modelled tidal generated flow discharge at Kanaishisa for Year 1-3 (top) and Year 4-6 (bottom) without TRM. Discharge is defined positive for upstream directed flow.

The gradual damping of the tidal generated discharge can also be illustrated and quantified by calculating the annual time-averaged gross discharge, i.e. averaging the absolute value of the flow discharge. Table 4.2 shows how the time-averaged gross discharge decreases over time due to gradual siltation of the branch and increased flow resistance. There is only a slight difference between the numbers for Year 1 and 2. This can be explained by the morphological adjustment of the initial bathymetry, which improves the conveyance of the system and thereby counteracts the impact of siltation. In the following years the decrease in gross discharge is only (mainly) related to the impact of siltation and thereby larger.

Table 4.2 Development of annual time-averaged gross discharge at Ranai, Katakhali, and Kanaishisa without TRM.

Cyclic period	Ranai [m^3/s]	Katakhali [m^3/s]	Kanaishisa [m^3/s]
Year 1	51.1	32.1	12.3
Year 2	50.4	31.3	12.2
Year 3	46.3	28.0	10.5
Year 4	41.8	24.6	9.2
Year 5	37.8	21.7	8.2
Year 6	34.4	19.5	7.5

Figure 4.21 shows the initial bathymetry of the Hari River branch and the morphological development of bed levels the following six years (cycles). The gradual siltation of the branch can be seen from the gradual downstream migration of the blue colour representing the highest bed levels. The presented bed levels are referring to m PWD.

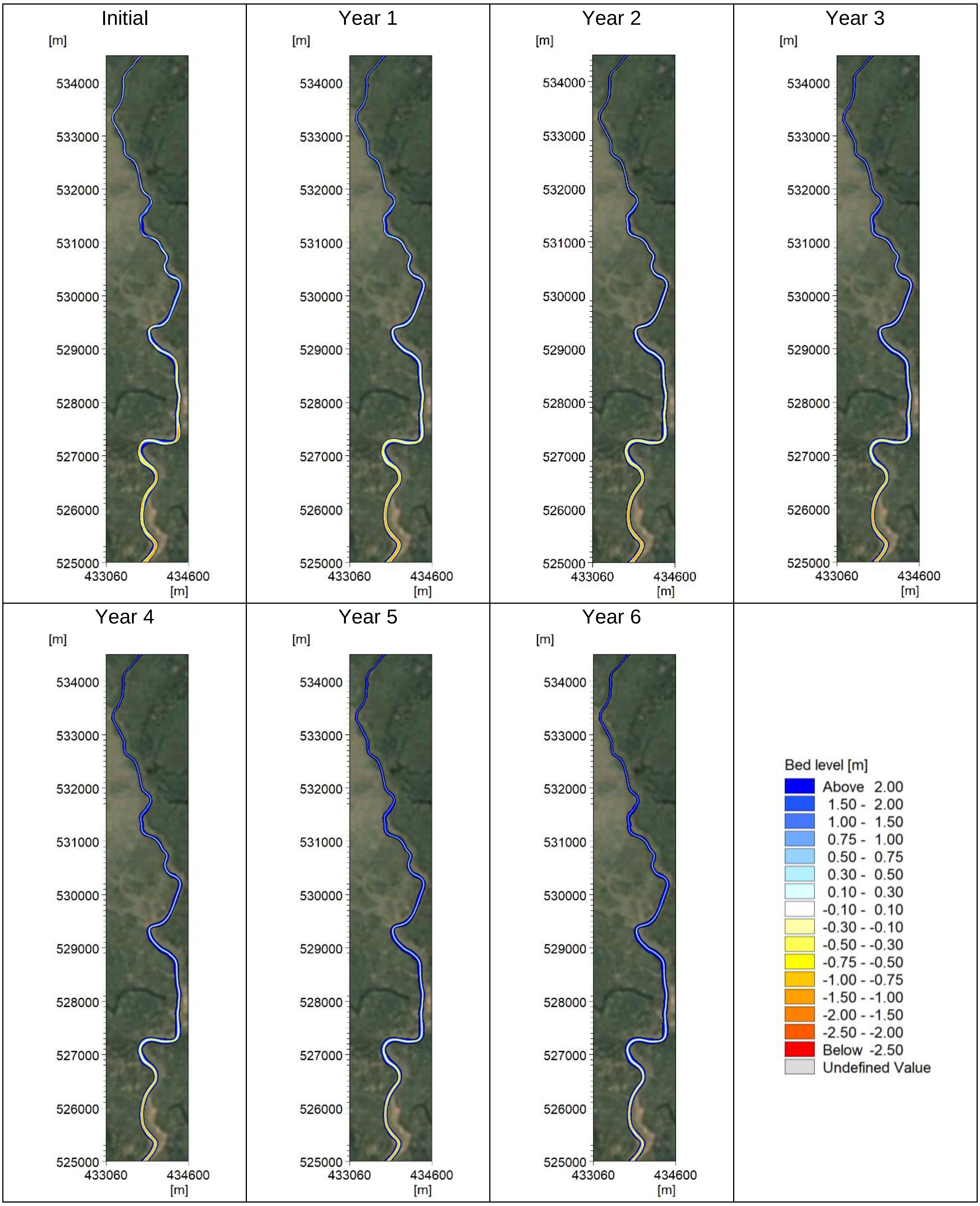

Figure 4.21 Bed level development of Hari River without TRM in the consecutive period of 6 years.

Figure 4.22 shows the bed level changes over time. The blue colours represent areas with deposition, while the red and yellow areas represent erosion. The morphological adjustment of the initial bathymetry is quite easy to identify when looking at the image for Year 1. At some reaches in the southern part erosion is the dominating mechanism to begin with.

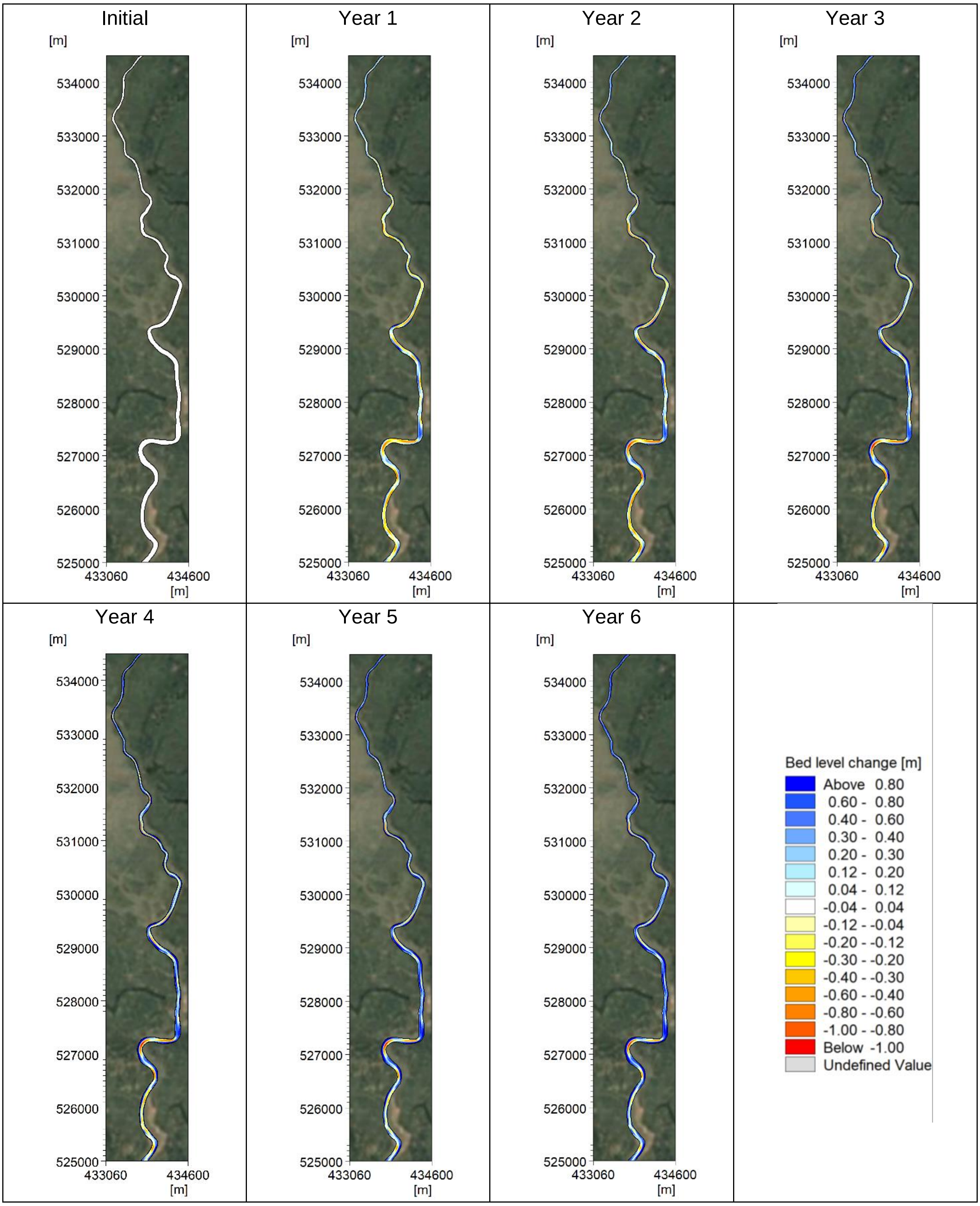

Figure 4.22 Bed level changes without TRM over a period of 6 years.

Figure 4.23 shows the annual sedimentation and erosion in the Hari River branch. The transition into a general siltation area after the morphological adjustment of the initial bathymetry is clearly seen in the plots for Year 3 to Year 6 that only contain the white and light blue colours.

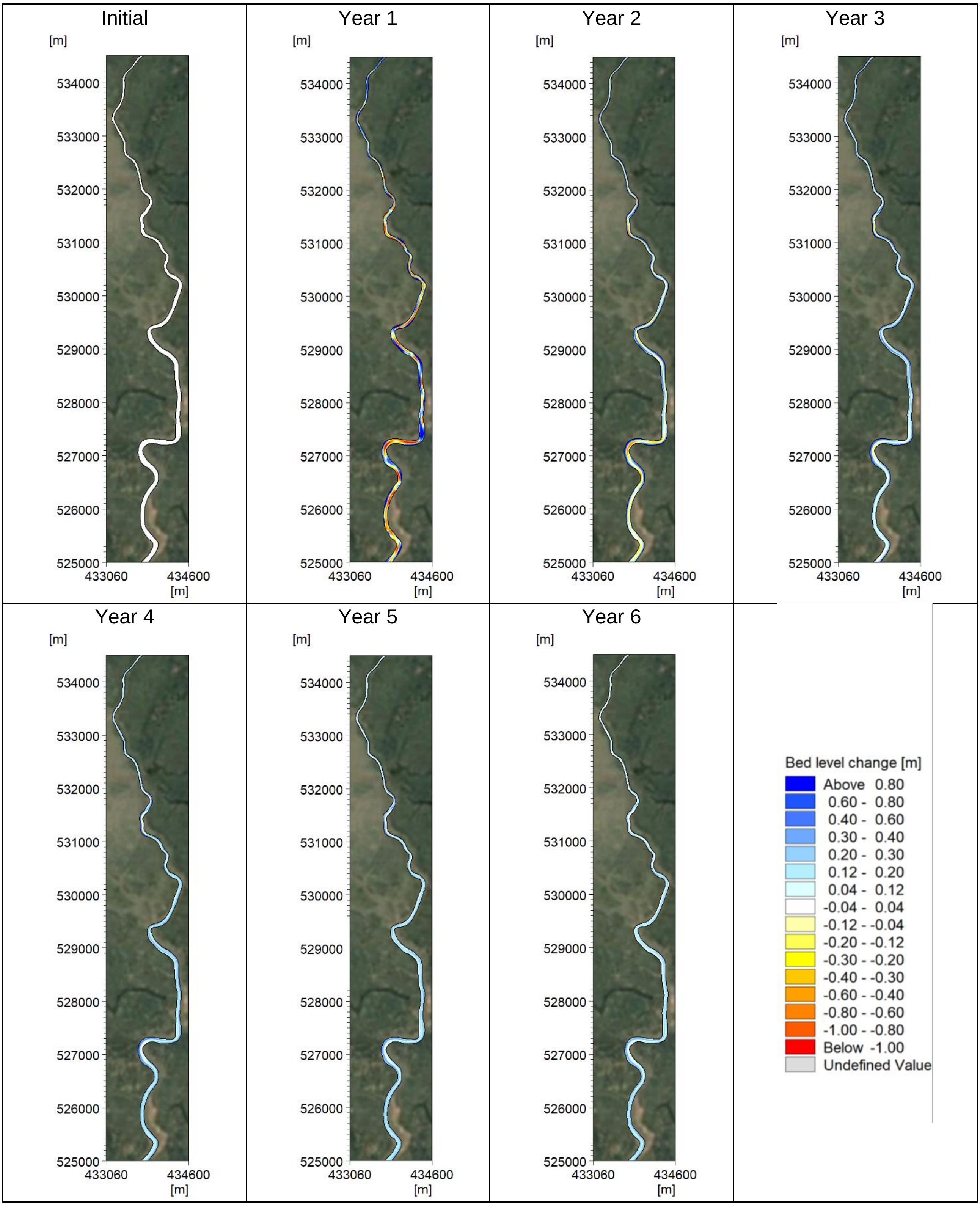

Figure 4.23 Annual bed level changes without TRM over a period of 6 years.

The temporal development of the upstream directed annual net sediment transport is shown in Figure 4.24 to Figure 4.26 for the cross sections at Ranai, Katakhali, and Kanaishisa. It is seen that the largest net sediment transport is obtained for Year 3 at Ranai and Katakhali, and for Year 2 at Kanaishisa. This indicates that the internal adjustment of the initial bathymetry plays a role for a longer period than revealed from the development of the gross discharges.

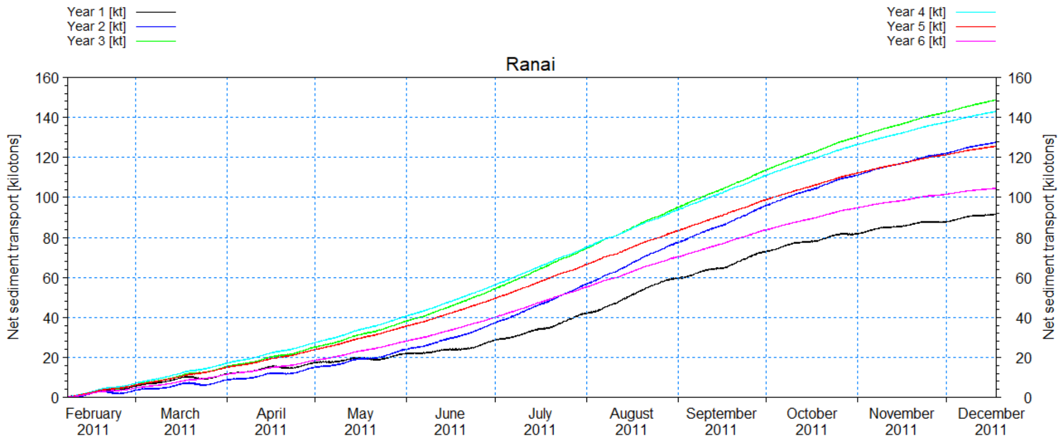

Figure 4.24 Net sediment transport (upstream directed) at Ranai for each of the 6 consecutive years.

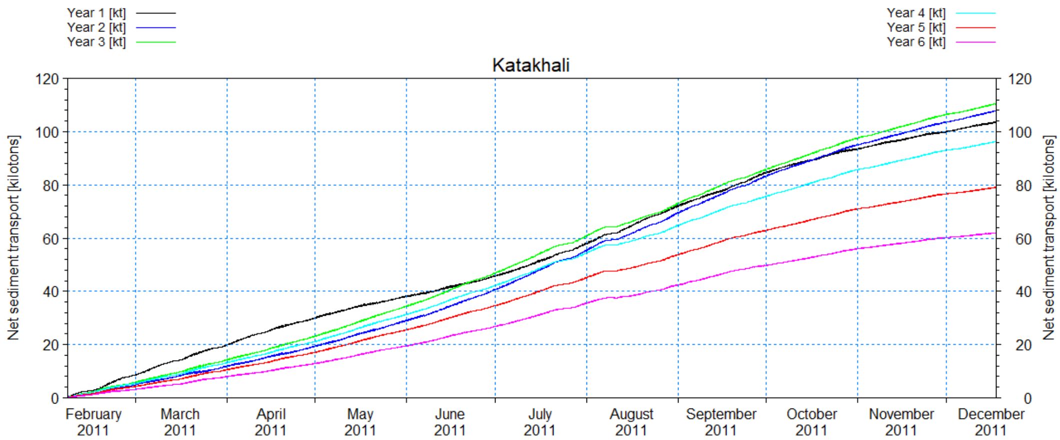

Figure 4.25 Net sediment transport (upstream directed) at Katakhali for each of the 6 consecutive years.

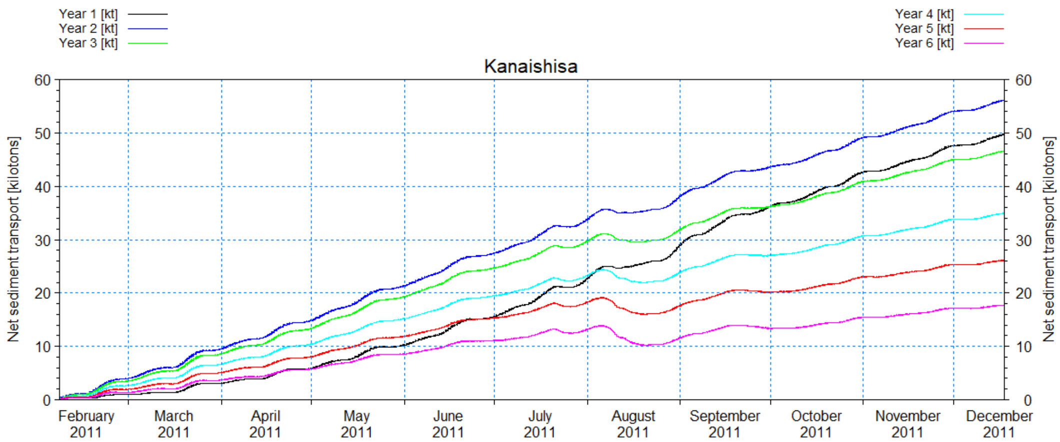

Figure 4.26 Net sediment transport (upstream directed) at Kanaishisa for each of the 6 consecutive years.

The calculated net sediment transport for each of the six cycles is listed in Table 4.3 for the cross sections at Ranai, Katakhali, and Kanaishisa. The net sediment transport at Katakhali is greater than the transport at Ranai in Year 1 even though Katakhali is located further upstream, where the tidal prism is larger. This behaviour can thereby only be explained by an increased transport related to an internal adjustment of the initial bathymetry.

Table 4.3 Net sediment transport per cyclic period at Ranai, Katakhali, and Kanaishisa.

Cyclic period	Ranai [kilotons]	Katakhali [kilotons]	Kanaishisa [kilotons]
Year 1	91.6	103.6	49.7
Year 2	127.6	107.8	56.1
Year 3	148.7	110.4	46.6
Year 4	143.0	96.2	34.9
Year 5	125.6	79.0	26.1
Year 6	104.5	61.9	17.7

The gradual siltation of the river branch can also be illustrated by the diagram (hypsometric curve) shown in Figure 4.27. The diagram shows the area inside the Hari River branch below a certain bed level for the initial bathymetry and after each of the six morphological cycles. The diagram clearly shows the gradual buildup of the bed caused by the upstream directed net sediment transport induced by tidal asymmetry and modest runoff.

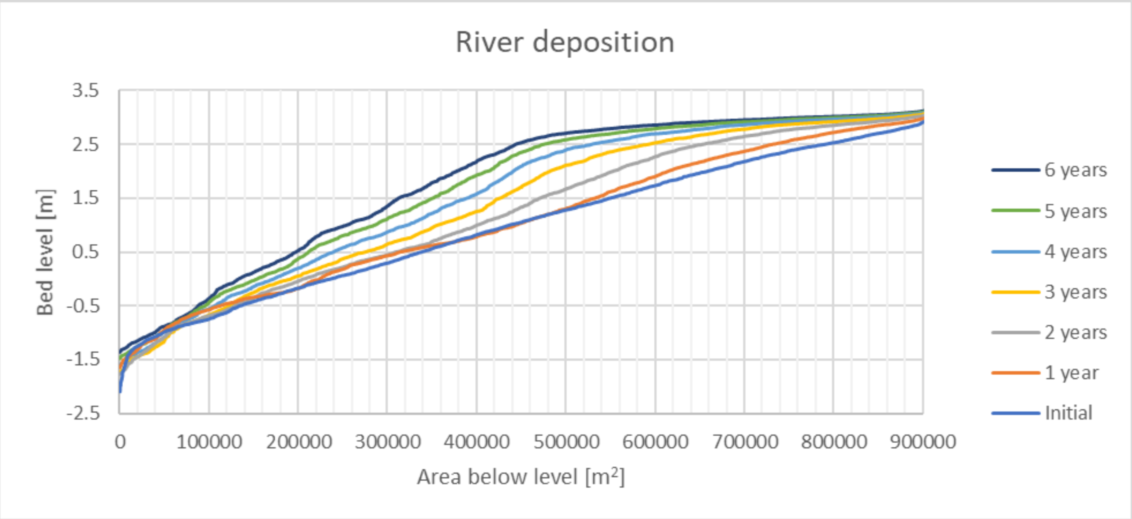

Figure 4.27 Area inside Hari River branch below a certain bed level without TRM over a period of 6 years.

4.5.2 TRM with an Opening in the Southern End of the Beel

The time scales and optimal lifetime for TRM operation have been examined using the TRM basin in Polder 24 (East Beel Khuksia) as conceptual test case. By using the cyclic morphological approach covering a period of almost 6 years annual impact is estimated and identified for both polder and peripheral river branch.

For conditions with TRM the opening into the polder will increase the tidal prism significantly and thereby introduce erosion of the peripheral river and deposition inside the polder due to the inflow of sediment laden water. The opening into the polder will to a large degree control the exchange of water and sediment between the peripheral river and the polder. The opening and entrance channel cross section geometry and area can be maintained fixed if constructed by concrete blocks able to resist erosion. However, this will not allow the opening to adapt morphologically to the capacity of the polder. For the present modelling the channel width is maintained but allowed to erode.

When running a morphological model, the flow conductivity usually increases due to a smoothing and adaptation of the initial bathymetry compared to running the model with a fixed bed and no adaptation. The morphological development in the first year does thereby both include the morphological changes related to the polder opening dynamics, but also to the internal morphological adjustment of the initial bathymetry of the Hari River branch.

The tidal generated flow discharge at Ranai, Katakhali, Kanaishisa and at the Polder S entrance is shown in Figure 4.28 to Figure 4.31. It is seen how the largest amplification takes place in the first year due to significant erosion of the peripheral Hari River. The tidal generated discharge peaks in Year 2-3, whereafter it decreases due the initiation of siltation in the peripheral river.

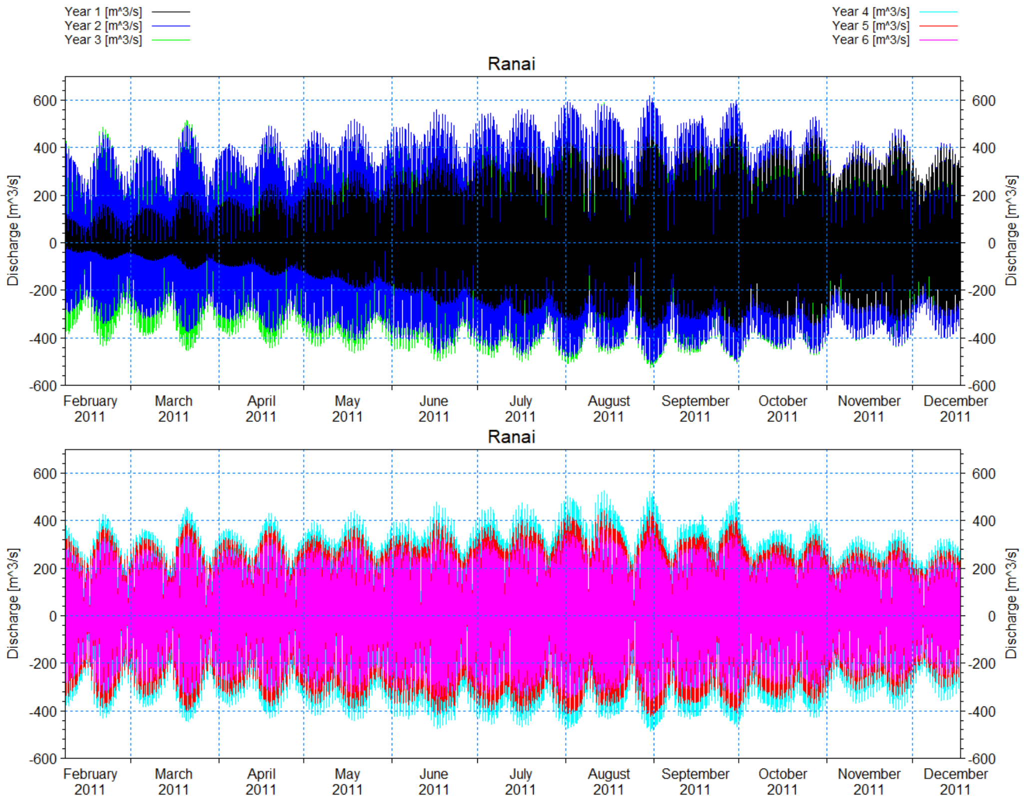

Figure 4.28 Modelled tidal generated flow discharge at Ranai for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for upstream directed flow.

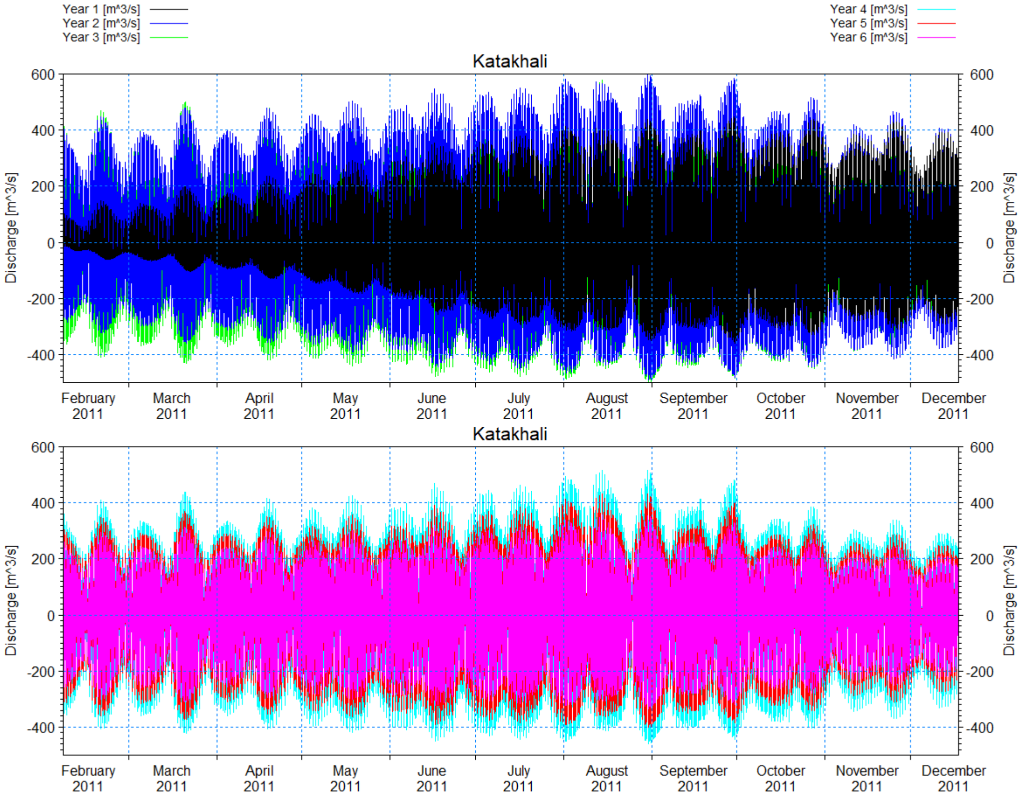

Figure 4.29 Modelled tidal generated flow discharge at Katakhali for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for upstream directed flow.

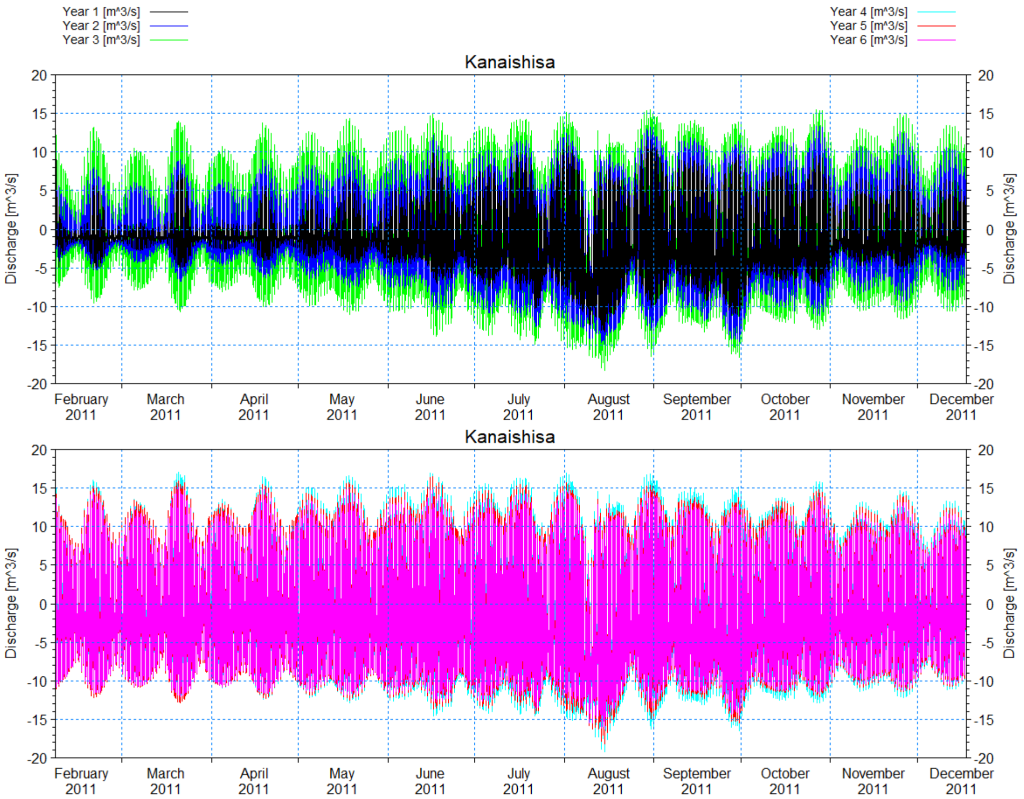

Figure 4.30 Modelled tidal generated flow discharge at Kanaishisa for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for upstream directed flow.

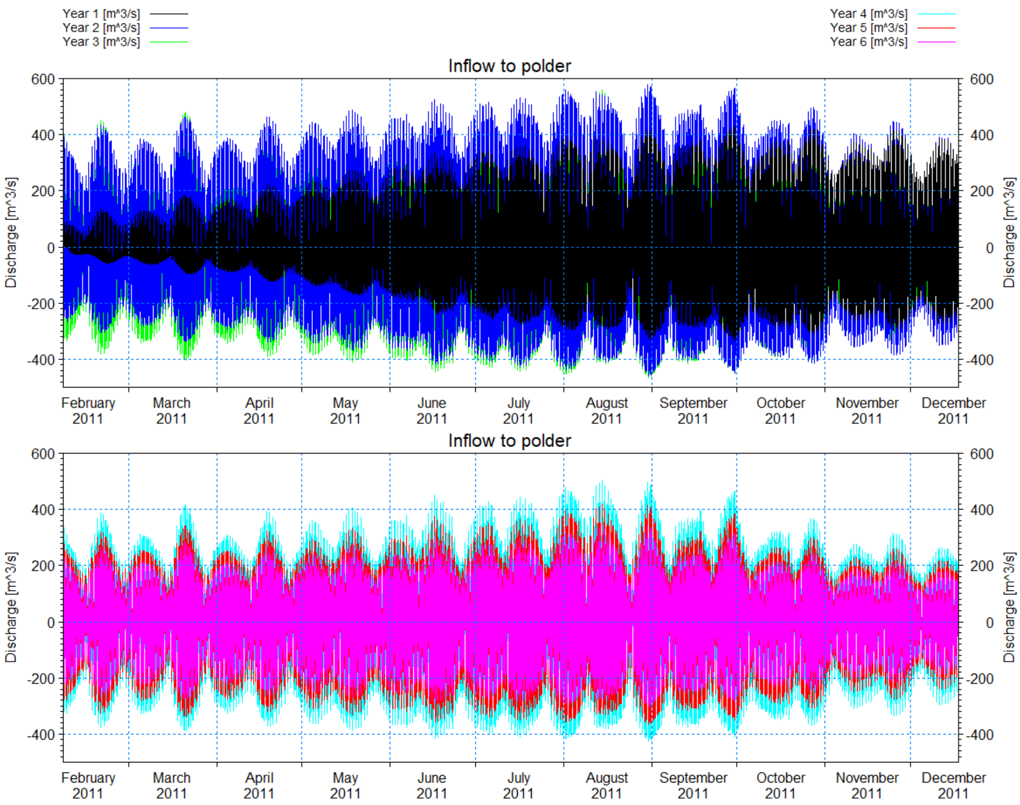

Figure 4.31 Modelled tidal generated flow discharge at Polder S for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for inflow to polder.

The significant amplification of the tidal generated discharge due to the increase of the tidal prism when opening into the polder is quantified and illustrated in Table 4.4 by calculating the annual time-averaged gross discharge.

Table 4.4 Development of annual time-averaged gross discharge at Ranai, Katakhali, and Kanaishisa with TRM and opening at the southern end.

Cyclic period	Ranai [m³/s]	Katakhali [m³/s]	Kanaishisa [m³/s]	Polder S [m³/s]
Year 1	167.7	162.8	3.2	156.2
Year 2	279.2	267.5	4.8	252.3
Year 3	277.7	261.6	6.3	241.3
Year 4	244.4	227.0	7.4	204.4
Year 5	206.1	188.4	7.2	166.1
Year 6	171.3	153.9	6.7	132.2
Year 1 without TRM	51.1	32.1	12.3	

To clarify the significant amplification of the annual time-averaged gross discharge the numbers for the first year without TRM is inserted in the end row in the table. Kanaishisa is located upstream the southern polder opening. The gross discharge at Kanaishisa is therefore quite low and actually less than obtained for the system without TRM. This indicates that TRM amplifies the tidal generated discharge downstream the polder opening but reduces it upstream the opening. In the morphological simulations the entrance channel is defined alluvial and able to erode and thereby increase the initially defined cross section area. The gross discharge is therefore found to peak in Year 2 and thereafter slightly decrease due to the siltation inside the polder.

When selecting a beel for TRM, it can be a great advantage that it contains old branches from the time before the polders were established. The connection to old branches will ensure a high tidal envelope inside the polder and long reaches with floodplains where flood tide can enter with sediment laden flow. The opening in the southern end of the beel is located near an old main channel. This opening is therefore found to have favourable conditions for TRM.

The tidal envelope, i.e. maximum water level minus minimum water level is illustrated in the following three figures. Figure 4.32 shows the minimum water level inside the polder and the peripheral river and Figure 4.33 the maximum water level for each of the six morphological cycles. The minimum water level plots show how the main channel and formation of side channels helps to penetrate the different areas of the polder and gradually moves the deposition areas towards north and east.

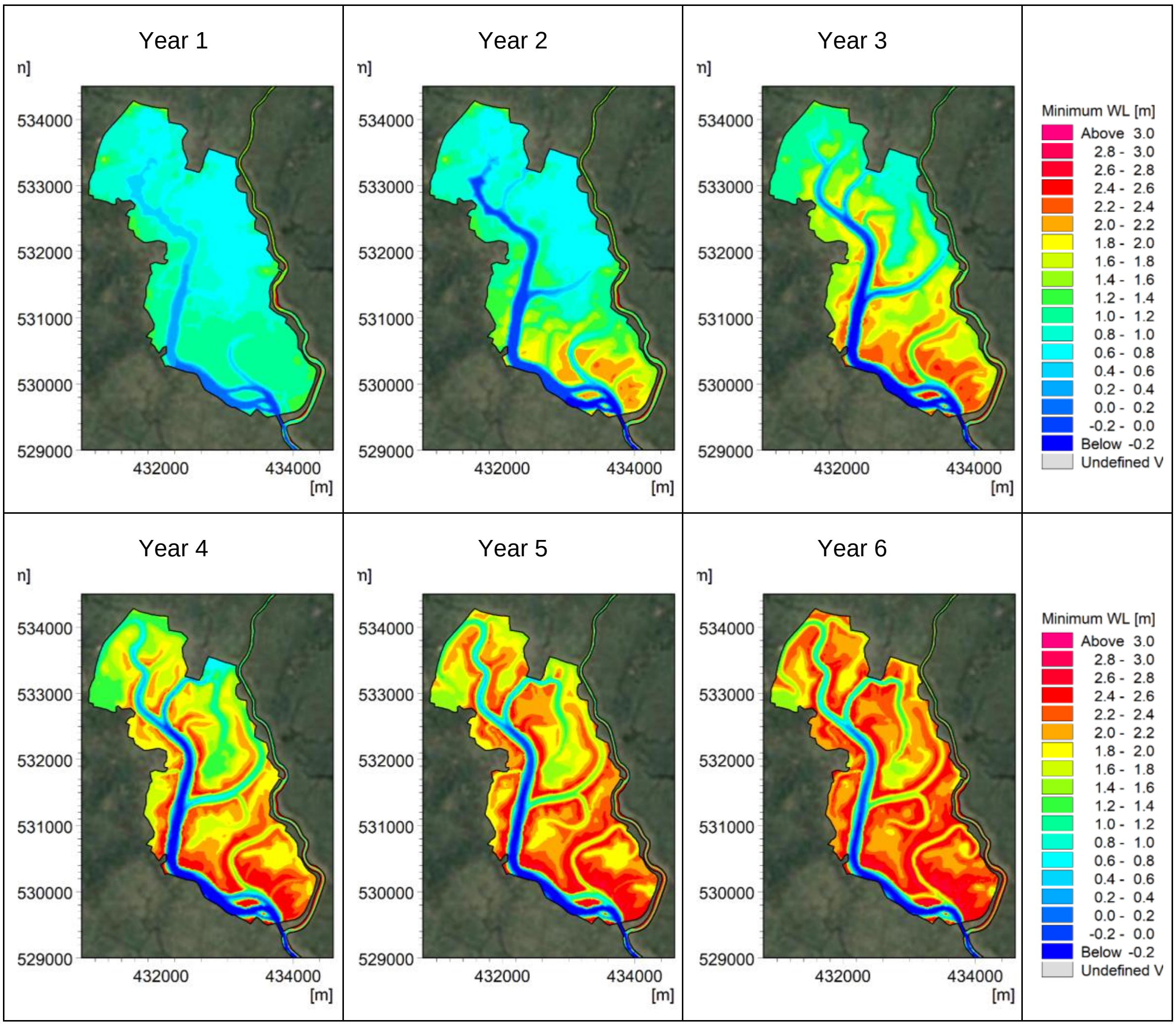

Figure 4.32 Minimum water level after activation of TRM at the southern end of the polder in the consecutive period of 6 years.

The maximum water level plots show mainly that the entire polder is being flooded at some point in time during each cycle. Furthermore, it is seen that the tidal maximum inside the beel is reached in Year 3.

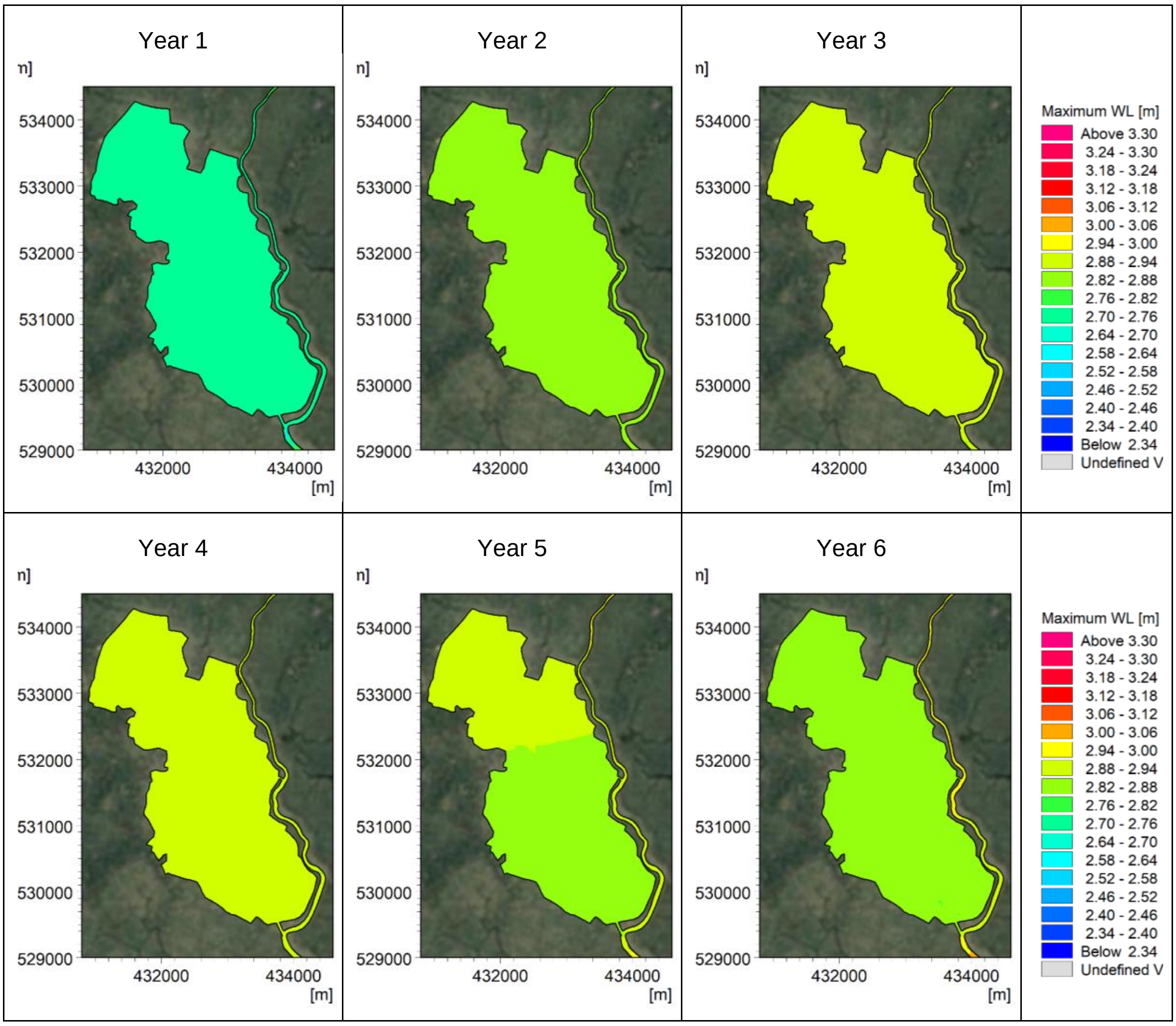

Figure 4.33 Maximum water level after activation of TRM at the southern end of the polder in the consecutive period of 6 years.

The temporal development of the tidal envelope is illustrated in Figure 4.34. A large tidal envelope inside the polder is important to maintain and ensure a significant sediment inflow to the entire polder. The images show how the tidal envelope is amplified in the side channels further to the north when the deposition in the southern part no longer can be flooded. The tidal envelope charts do also provide information on the drainage ability of the beel after closing the polder and stopping the TRM operation.

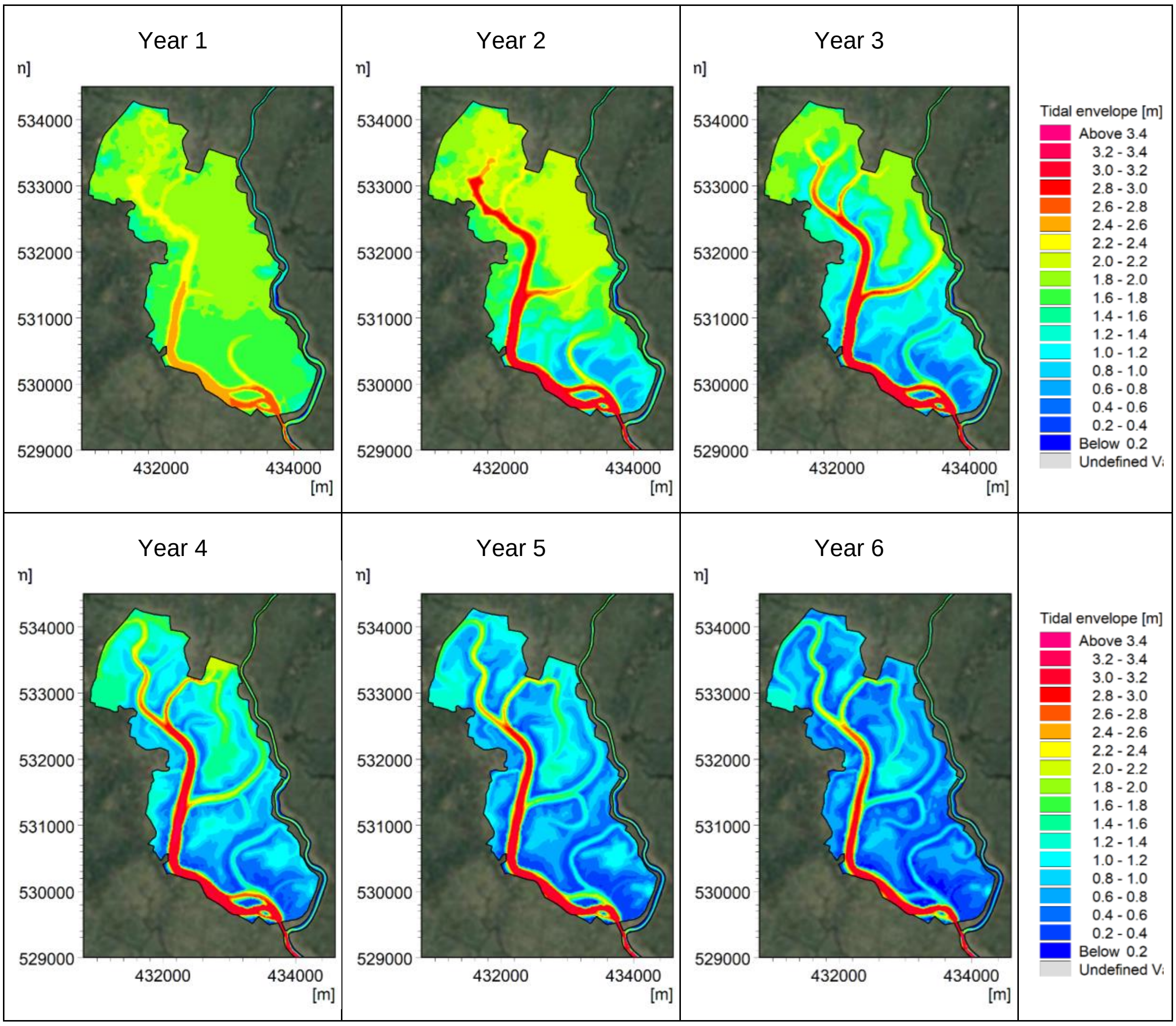

Figure 4.34 Tidal envelope after activation of TRM at the southern end of the polder in the consecutive period of 6 years.

One of the main purposes of TRM is to prevent drainage congestion. It is therefore of relevance to look at the temporal development of the tidal range at a location in Hari River just downstream the opening into the polder. Figure 4.35 shows how the tidal range is increased over time due the activation of TRM. It is the level of the ebb tide that controls the drainage ability of the beel/polder. From the plot it is seen that this improvement is achieved already in the second year of operation.

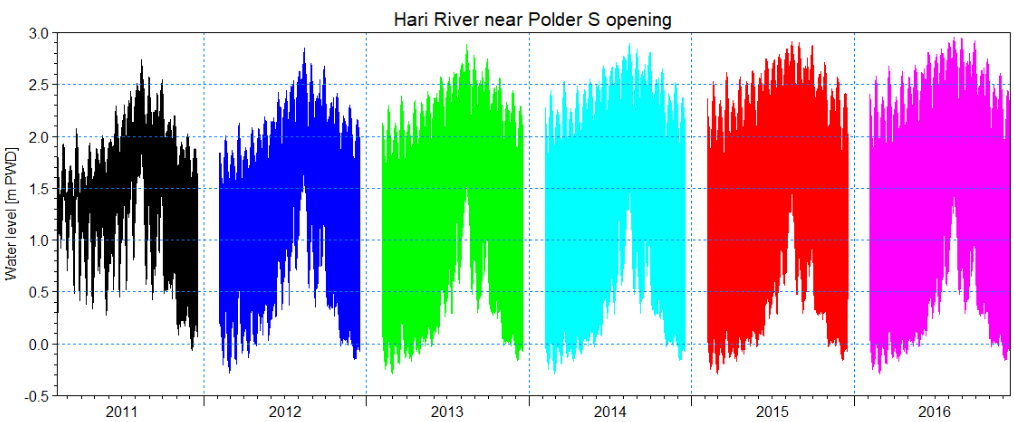

Figure 4.35 Tidal variation in Hari River near the polder opening after activation of TRM.

Figure 4.36 shows the initial bathymetry of the polder and the Hari River branch and the morphological development of bed levels the following six years after the opening into the southern part of the polder. The gradual build-up of the bed to levels above 2 m PWD and migration towards north and east is clearly seen from the images.

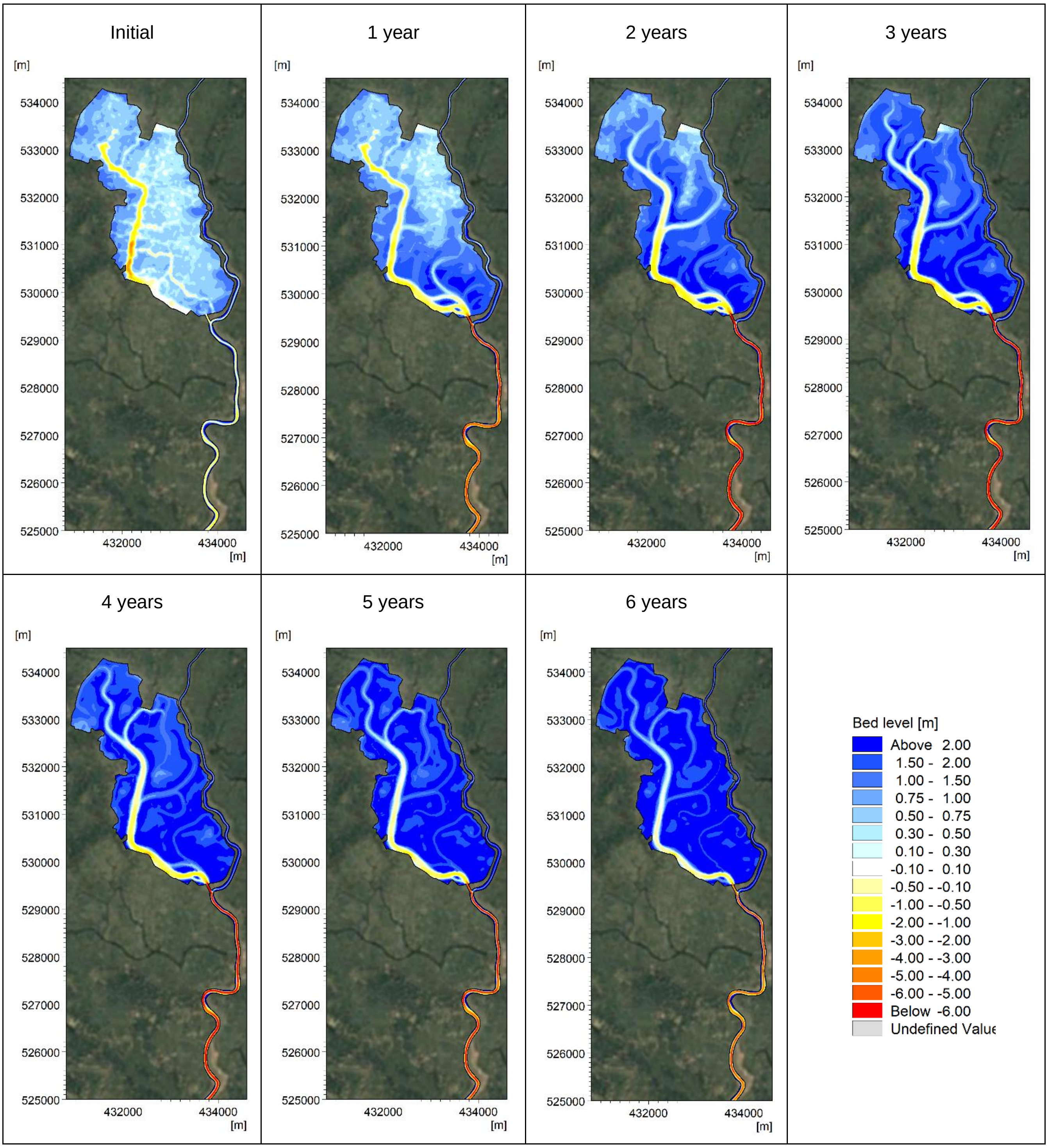

Figure 4.36 Bed level development after activation of TRM at the southern end of the polder in the consecutive period of 6 years.

The corresponding plots showing the accumulated bed level changes are shown in Figure 4.37. From the plots, it is seen how the siltation pattern gradually migrate into the polder during the first 3 years. The presence of an old channel network makes it possible for the sediment being flushed to penetrate far inside the polder and distributed into the floodplains, where calm flow conditions allow sediment to settle. The plots also show a significant erosion taking place inside the Hari River branch downstream the opening into the polder. Erosion is also taking place in parts of the channel network inside the polder. This erosion is important to maintain the flushing ability of the polder and capability to penetrate water and sediment into the entire polder. It is also important to prevent water logging in the future system when TRM is abandoned.

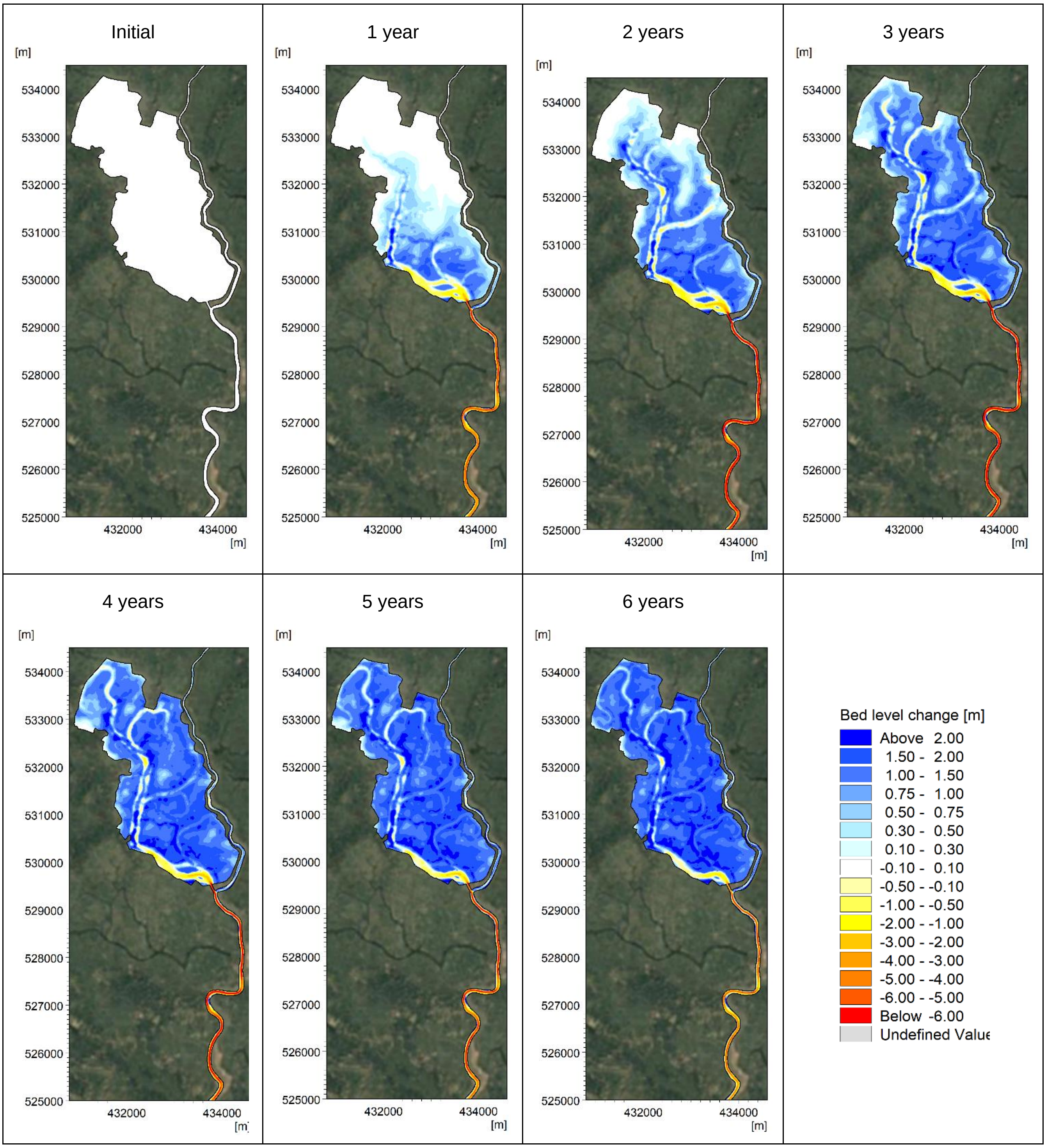

Figure 4.37 Bed level changes after activation of TRM at the southern end of the polder in the consecutive period of 6 years.

Figure 4.38 shows the annual sedimentation and erosion (i.e. for each cycle) inside the polder and the Hari River branch. It is seen that sediment is mainly settling in the southern part during Year 1. In Year 2 deposition is migrating to the middle part, while at the same time the channel network is eroding. In Year 3 settling are mainly taking place in the northern part of the polder. In this year the Hari River branch reaches an equilibrium, i.e. erosion has stopped. In year 4-6 the tidal volume of the polder is decreasing leading to siltation in the Hari River branch and the channel network inside the polder. The TRM has therefore lost its eligibility after 4 years.

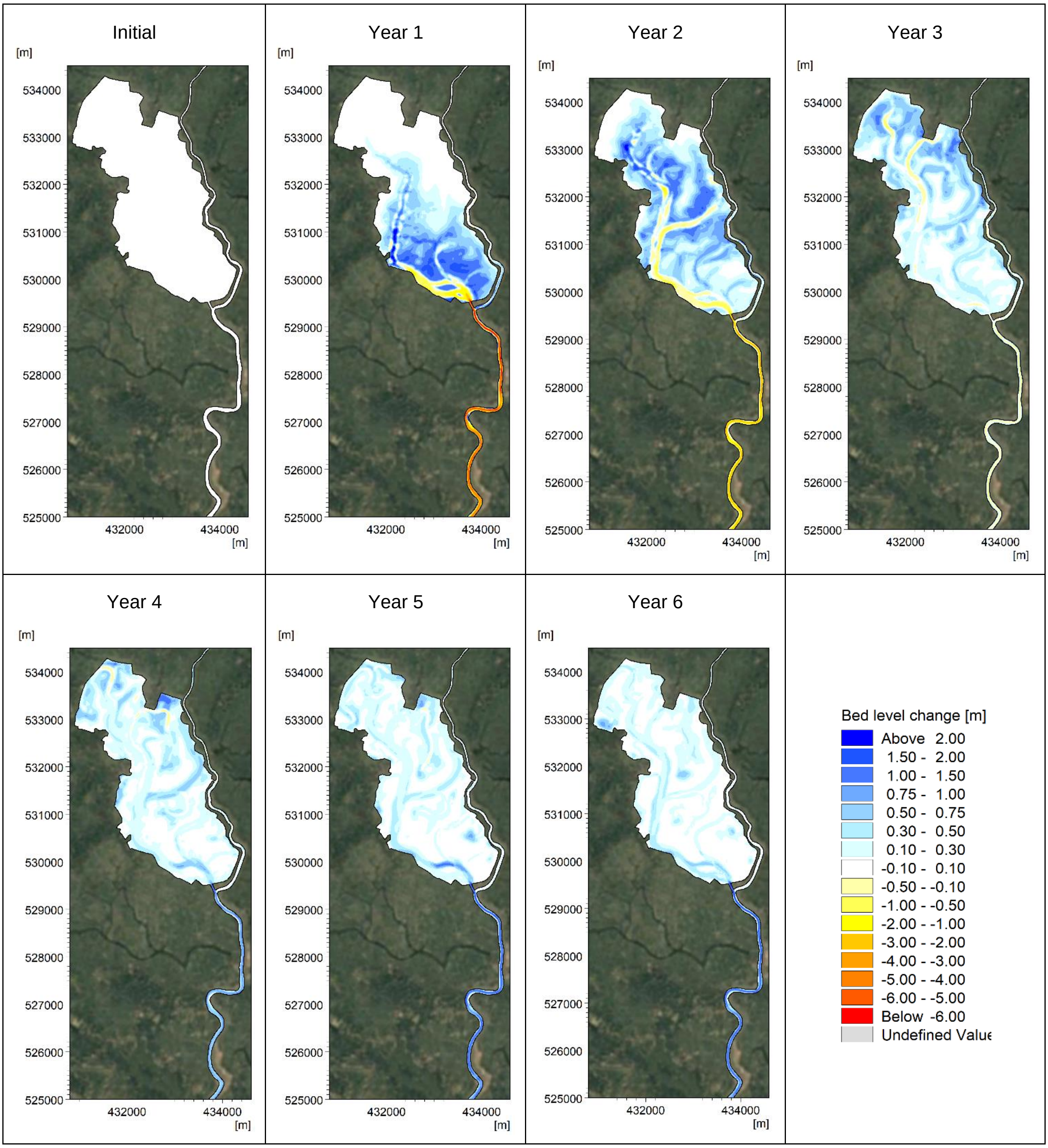

Figure 4.38 Annual bed level changes after activation of TRM at the southern end of the polder in the consecutive 6 years.

The temporal development of the upstream directed annual net sediment transport is shown in Figure 4.39 to Figure 4.42 for the cross sections at Ranai, Katakhali, Kanaishisa, and Polder S. It is seen that the largest net sediment transport is obtained for Year 2 at Ranai, Katakhali, and Polder S. Kanaishisa is located further upstream than the Polder S opening and thereby only weakly affected by the TRM.

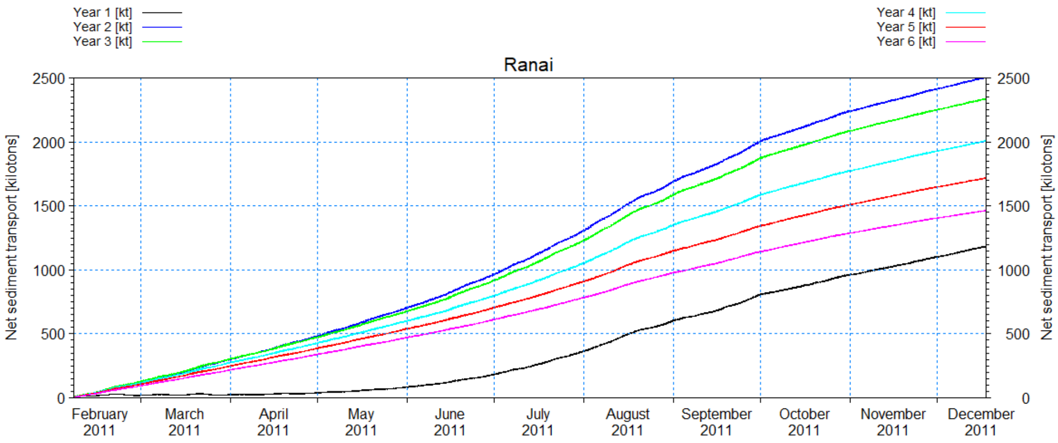

Figure 4.39 Net sediment transport at Ranai for each of the 6 consecutive years.

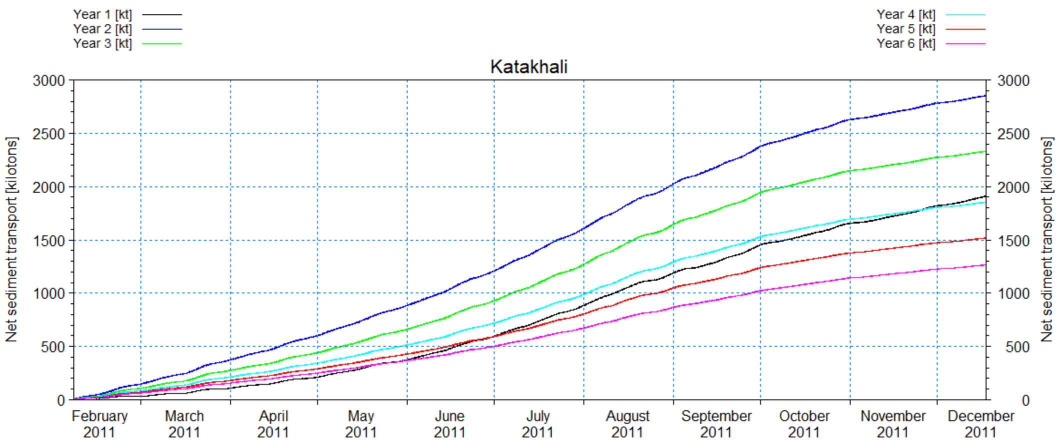

Figure 4.40 Net sediment transport at Katakhali for each of the 6 consecutive years.

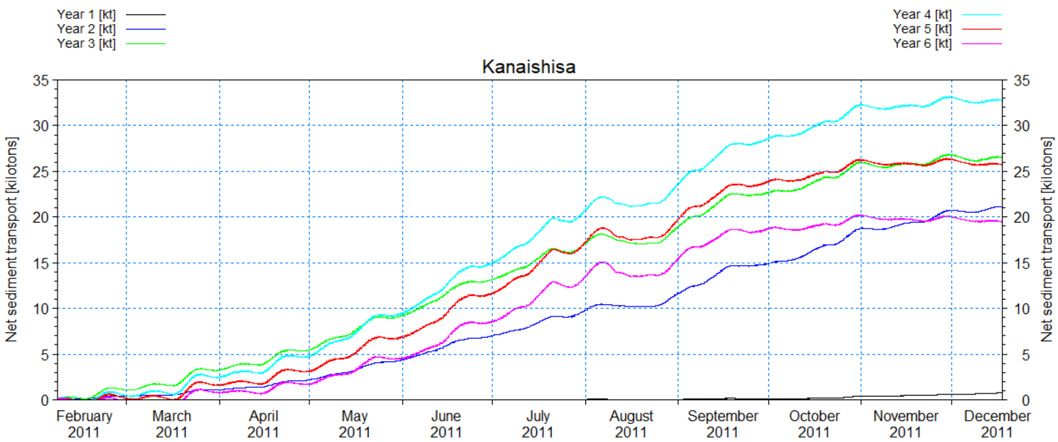

Figure 4.41 Net sediment transport at Kanaishisa for each of the 6 consecutive years.

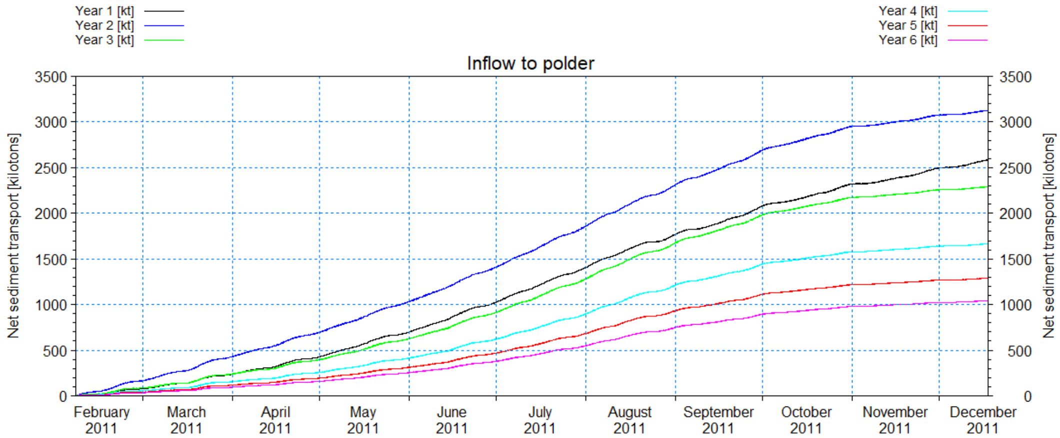

Figure 4.42 Net sediment transport at Polder S for each of the 6 consecutive years.

The calculated net sediment transport for each of the six cycles is listed in Table 4.5 for the cross sections at Ranai, Katakhali, Kanaishisa and Polder S. The net sediment transport at Katakhali is greater than the transport at Ranai in Year 1 and 2 due to the downstream migrating river erosion initiated by the opening to the polder and increased tidal prism. The beginning siltation of the river branch in Year 4 to 6 can also be revealed from the numbers in the table.

Table 4.5 Net sediment transport per cyclic period at Ranai, Katakhali, Kanaishisa, and Polder S.

Cyclic period	Ranai [kilotons]	Katakhali [kilotons]	Kanaishisa [kilotons]	Polder S [kilotons]
Year 1	1183	1909	0.7	2585
Year 2	2503	2852	21.1	3124
Year 3	2335	2330	26.5	2288
Year 4	2006	1853	32.8	1664
Year 5	1716	1517	25.7	1288
Year 6	1463	1264	19.5	1041

The achieved impact obtained by use of TRM is illustrated in Figure 4.43. The diagram shows the area inside the polder, which is located above a given bed level value for initial bathymetry and the consecutive 6 years. It is seen that it is primarily the first 3 years the TRM is well-functioning. Siltation is also taking place inside the polder in Year 4-6, but this is mainly in the drainage network, which is of severe importance for the operation of the polder after TRM operation has stopped. The diagram shows that it is almost the entire area of the beel which is elevated due to TRM. The TRM potential at a location like this is therefore very high and better than what has been achieved elsewhere.

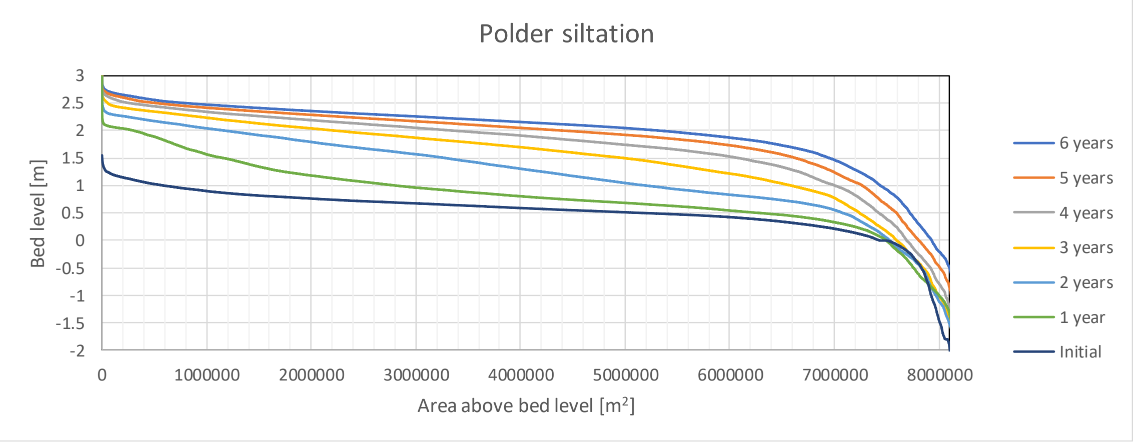

Figure 4.43 Area inside polder above a certain bed level during TRM operation.

A similar diagram (hypsometric curve) is made for the Hari River branch and shown in Figure 4.44, however in this case with focus on the deepest parts. It is seen that significant (but favourable) erosion takes place during the first year. The erosion continues in the two following years, but with less pace. In Year 4 sediment starts to settle in the river branch and the siltation continues in Year 5 and 6 as the tidal prism of the polder decreases.

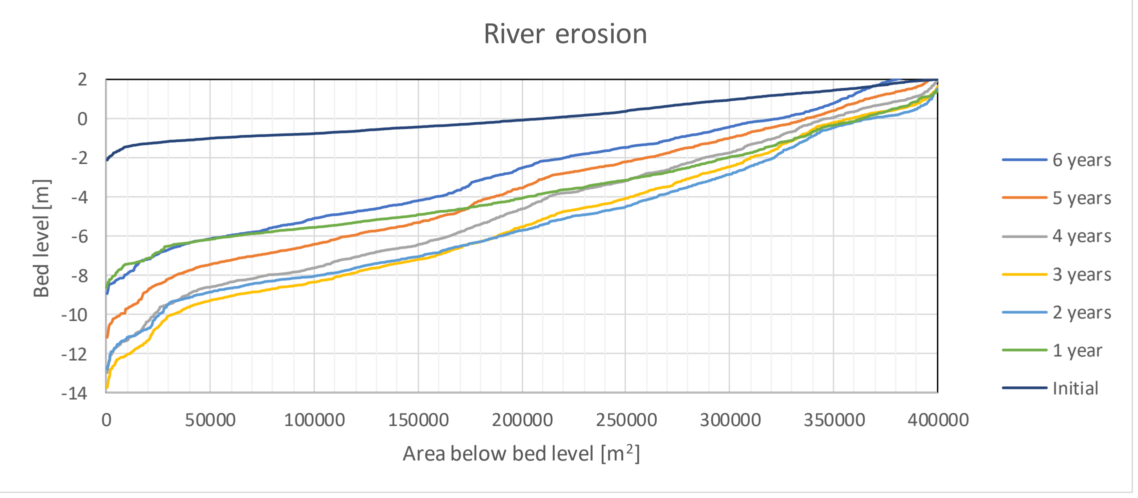

Figure 4.44 Area inside Hari River branch (downstream polder opening) below a certain bed level during TRM operation.

4.5.3 TRM with an Opening in the Eastern Side of the Beel

The opening at the eastern side of the beel is located further upstream than the opening in the south. The tidal generated discharges are therefore smaller at this location due to a smaller tidal prism (in the system without an opening). The bed levels inside the polder are relatively high in the area of the entrance channel and there is no nearby channels to help stimulating the tidal exchange. The location is not optimal compared to the southern opening, but it is examined since there historically also has been an opening at this location.

The tidal generated flow discharge at Ranai, Katakhali, Kanaishisa and at the Polder E entrance is shown in Figure 4.45 to Figure 4.48. It is seen how the largest amplification of the flow discharge takes place in the first two years due to the erosion of the peripheral Hari River. The tidal generated discharge peaks in Year 4 and 5, whereafter it decreases due the initiation of siltation in the peripheral river.

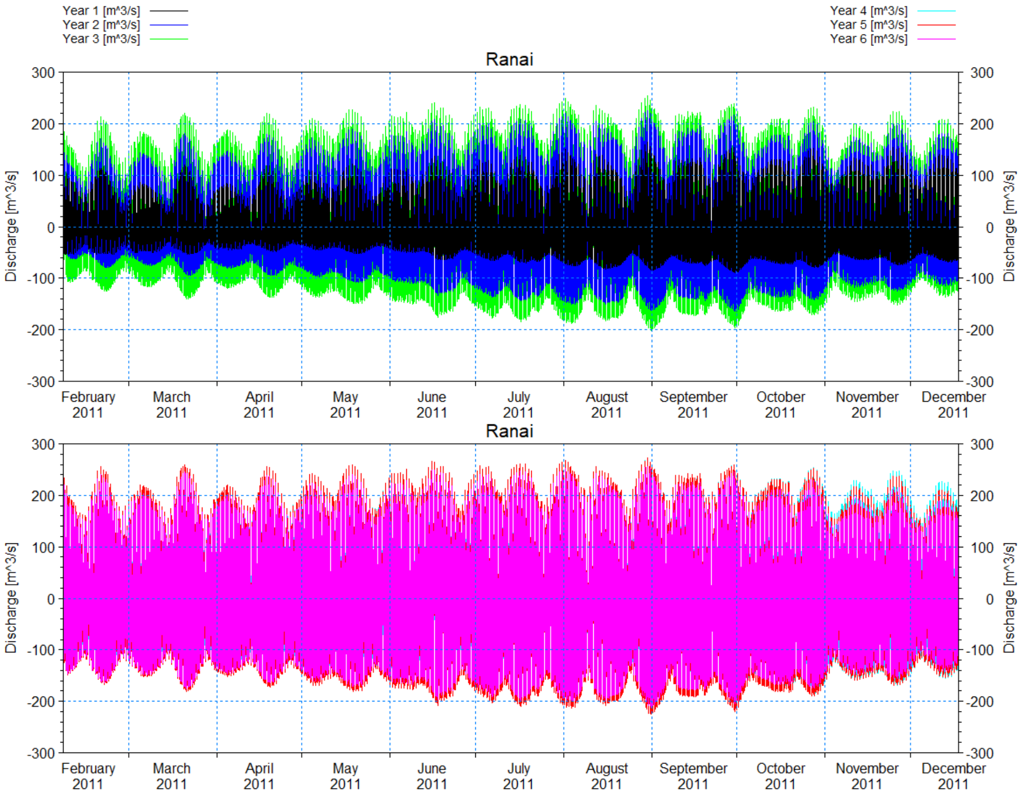

Figure 4.45 Modelled tidal generated flow discharge at Ranai for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for inflow to polder.

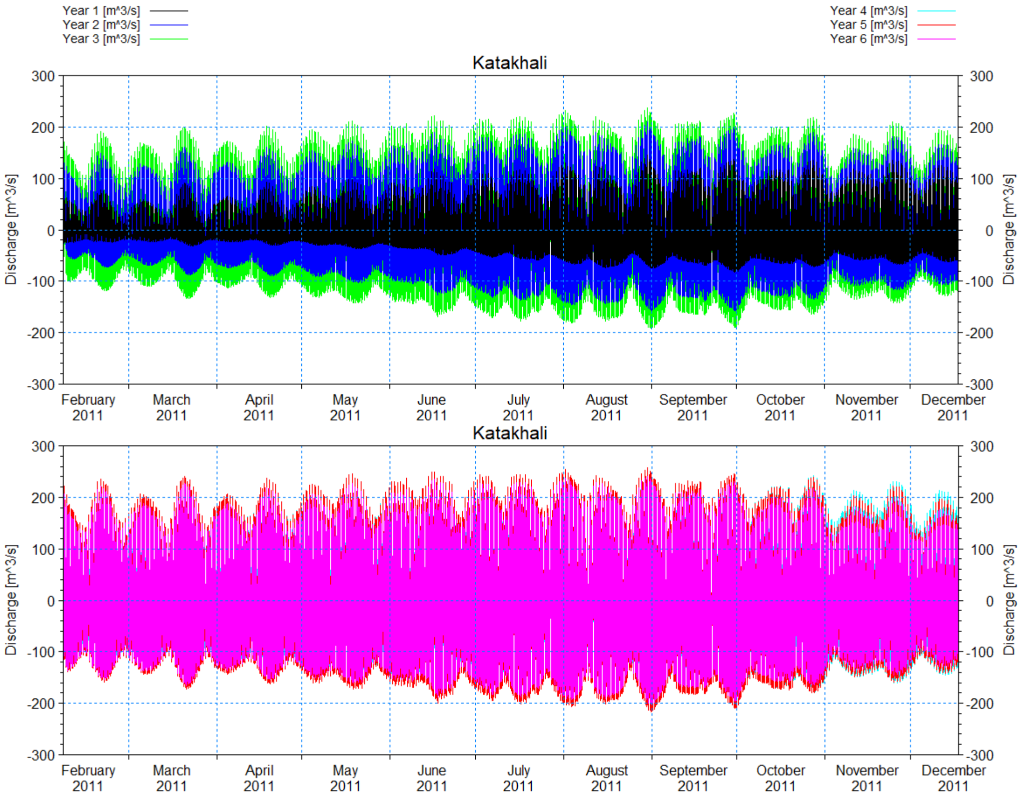

Figure 4.46 Modelled tidal generated flow discharge at Katakhali for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for inflow to polder.

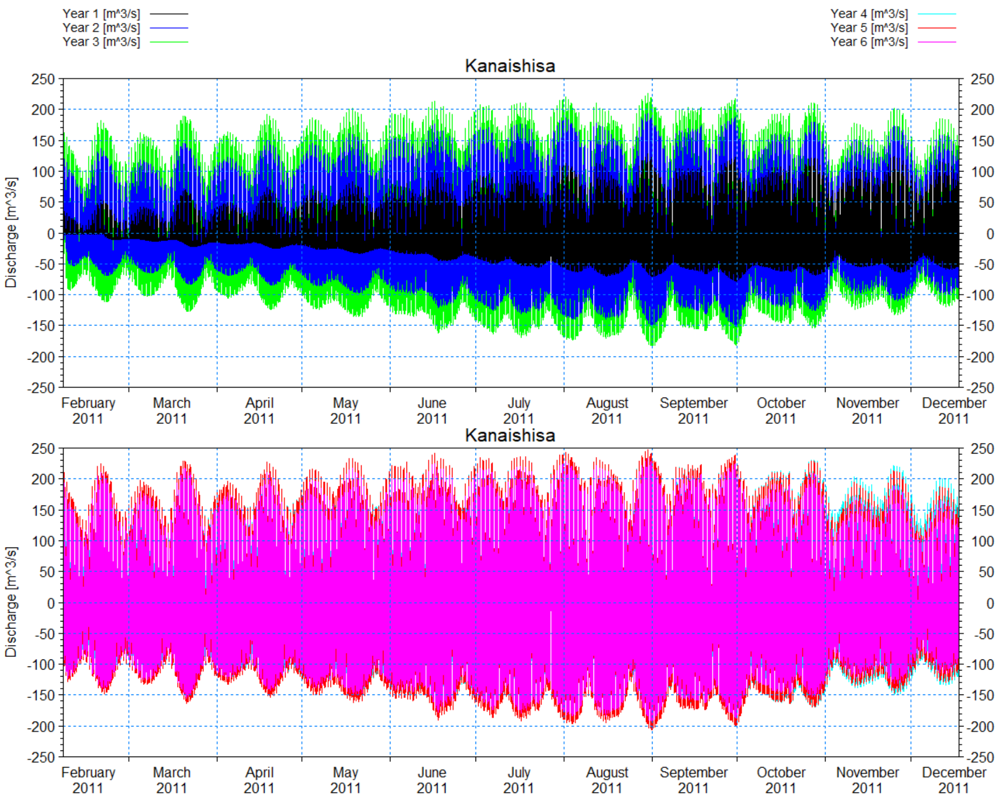

Figure 4.47 Modelled tidal generated flow discharge at Kanaishisa for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for inflow to polder.

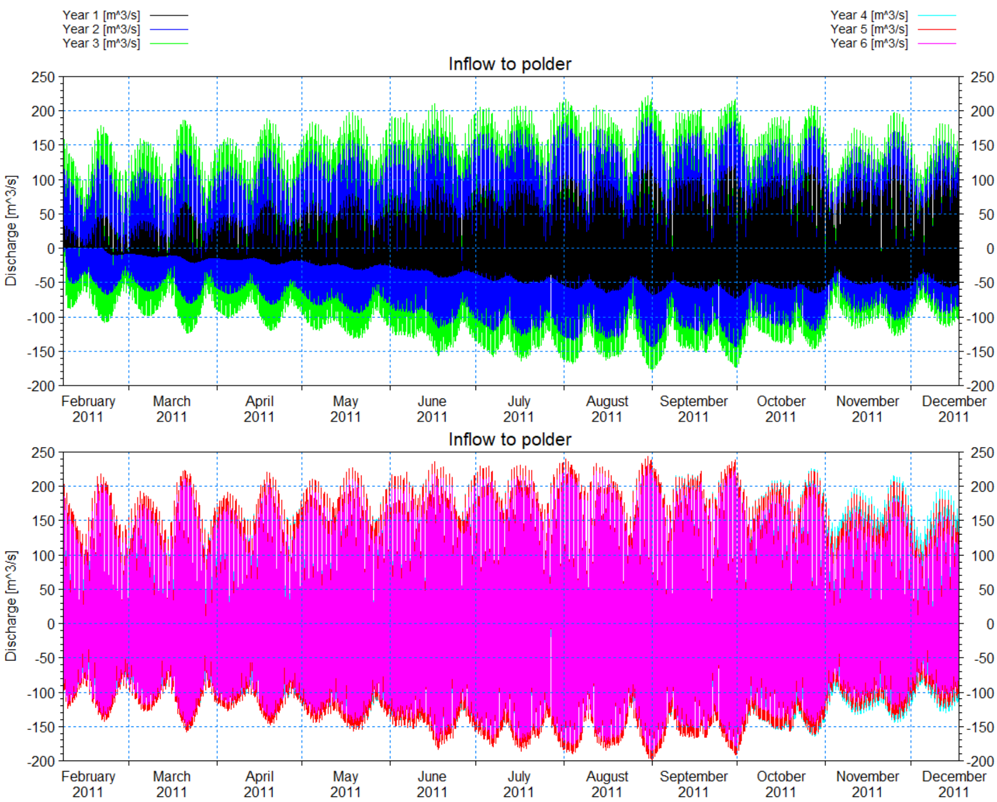

Figure 4.48 Modelled tidal generated flow discharge at Polder E for Year 1-3 (top) and Year 4-6 (bottom) with TRM and opening at the southern end. Discharge is defined positive for inflow to polder.

The significant amplification of the tidal generated discharge due to the increase of the tidal prism is quantified and illustrated in Table 4.6 by calculating the annual time-averaged gross discharge. To clarify the amplification of the annual time-averaged gross discharge the numbers for the first year without TRM is inserted in the end row. In the morphological simulations the entrance channel is defined alluvial and able to erode and thereby increase the initial cross section area. The gross discharge is therefore found to develop relatively slow and first peak in Year 4 or 5 (depending on the cross section) and thereafter slightly decrease due to the siltation of the area.

Table 4.6 Development of annual time-averaged gross discharge at Ranai, Katakhali, and Kanaishisa with TRM and opening at the eastern side.

Cyclic period	Ranai [m³/s]	Katakhali [m³/s]	Kanaishisa [m³/s]	Polder E [m³/s]
Year 1	47.9	40.4	37.4	36.5
Year 2	85.5	81.0	77.4	75.5
Year 3	108.7	104.0	100.0	97.6
Year 4	123.6	119.1	115.3	112.8
Year 5	127.3	121.3	115.6	112.4
Year 6	119.9	112.7	105.3	101.6
Year 1 without TRM	51.1	32.1	12.3	

When selecting a beel and a location for TRM, it can be a great advantage that it contains old branches from the time before the polders was established. The connection to old branches will ensure a high tidal envelope inside the polder and long reaches with floodplains, where flood tide can enter with sediment laden flow. While the opening in the southern end of the beel is located near an old main channel this is not really the case for the opening in the eastern side.

The tidal envelope, i.e. maximum water level minus minimum water level is illustrated in the following three figures. Figure 4.49 shows the minimum water level inside the polder and the peripheral river and Figure 4.50 the maximum water level for each of the six morphological cycles. The minimum water level plots show how the main channel and formation of side channels helps to penetrate the different areas of the polder and gradually moves the deposition areas towards north and east. However, the plots show that there are no channels inside the polder that could stimulate the tidal exchange except from the channel being eroded at the opening entrance and inwards.

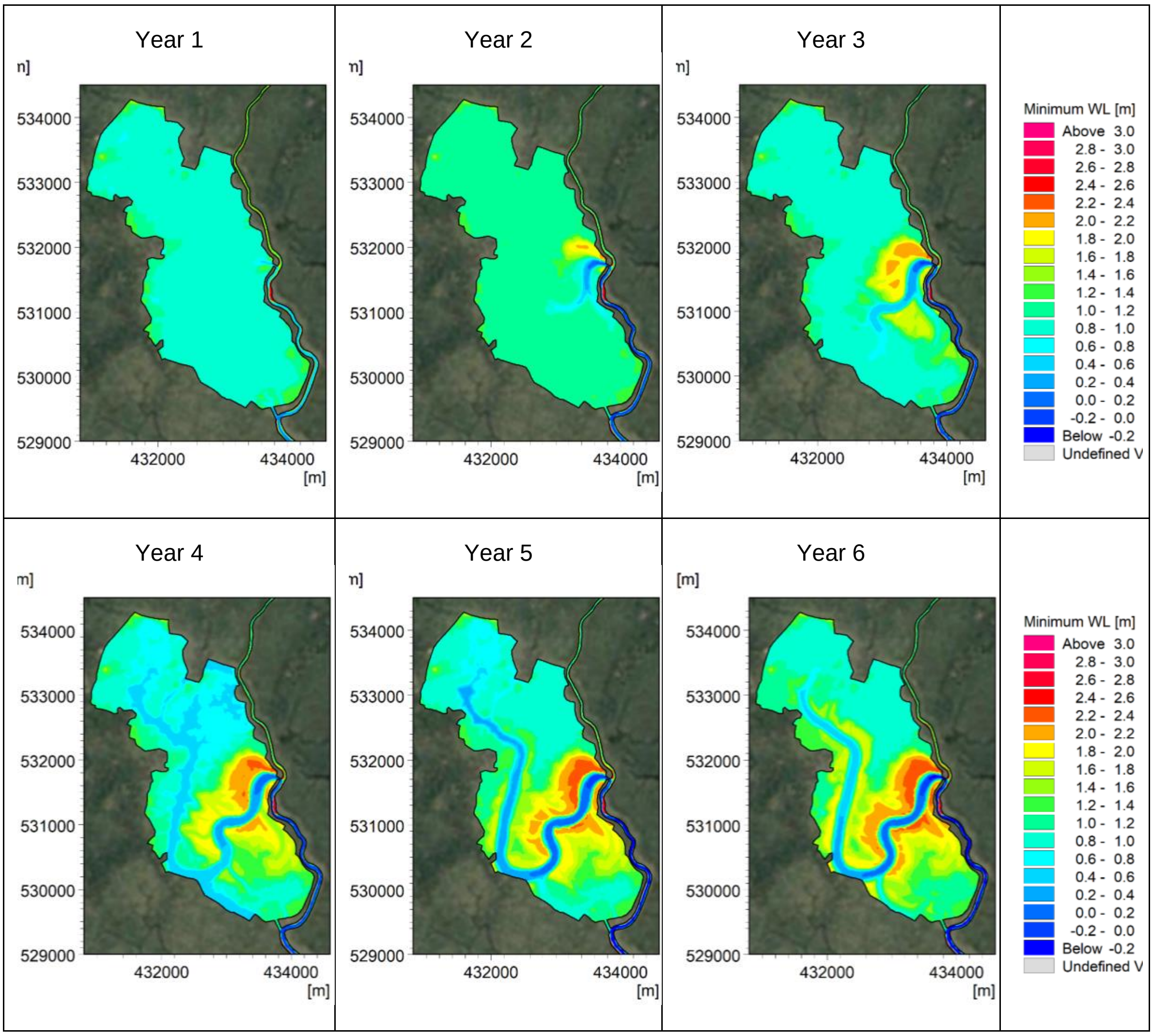

Figure 4.49 Minimum water level after activation of TRM at the eastern side of the polder in the consecutive period of 6 years.

The maximum water level plots show mainly that the entire polder is being flooded at some point in time during each cycle. Furthermore, it is seen that the tidal maximum inside the beel is reached in Year 3. It is also seen that the maximum water levels are smaller than what is achieved with an opening in the southern end. The efficiency of the TRM could have been improved if a channel connecting to the old channel network from before the polders were established had been pre-dredged.

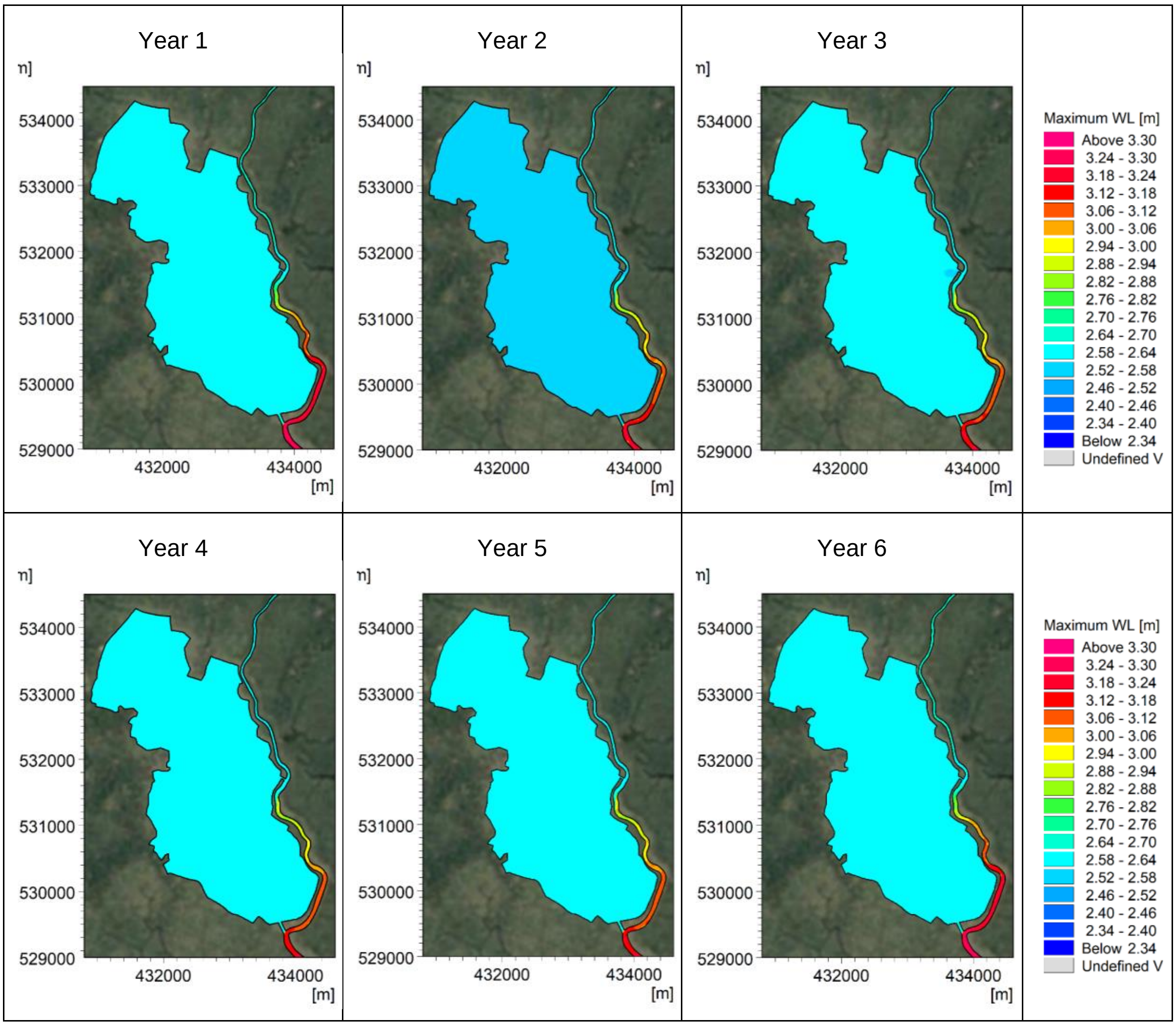

Figure 4.50 Maximum water level after activation of TRM at the eastern side of the polder in the consecutive period of 6 years.

The temporal development of the tidal envelope is illustrated in Figure 4.51. A large tidal envelope able to penetrate far inside the polder is important to maintain and ensure a significant sediment inflow to the entire polder and obtain a high TRM efficiency. The images show that the areas with a high tidal envelope only are related to the main channel. The lack of side channels limits the deposition to the nearby floodplain areas along with the main channel. The efficiency of the TRM is therefore not very good as compared to the scenario with an opening in the southern end. Pre-dredging or dredging inside the beel during the TRM operation to stimulate the generation of side channels seems to be a way forward to obtain and increased TRM efficiency.

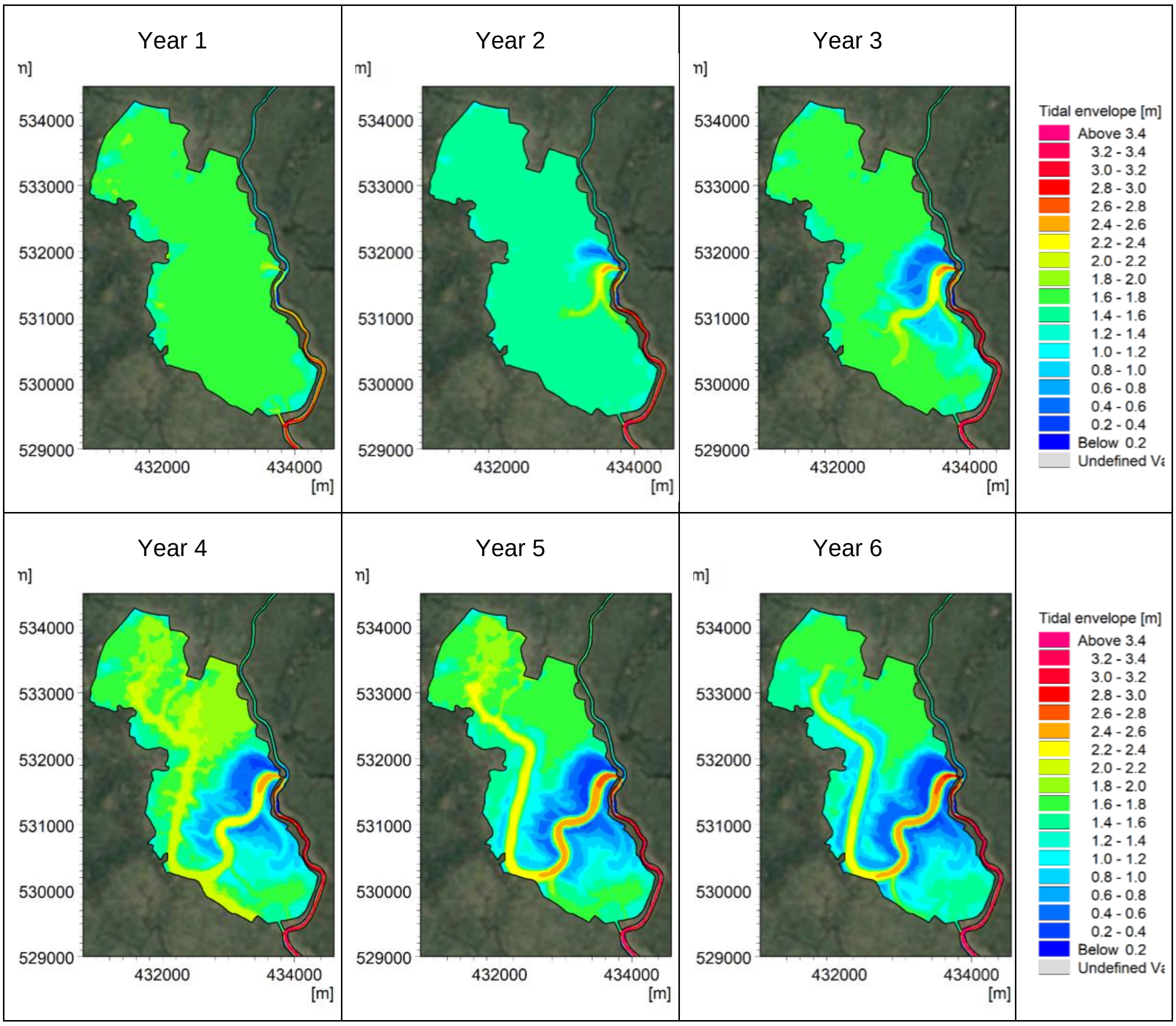

Figure 4.51 Tidal envelope after activation of TRM at the eastern side of the polder in the consecutive period of 6 years.

One of the main purposes of TRM is to prevent drainage congestion. It is therefore of relevance to look at the temporal development of the tidal range at a location in Hari River just downstream the opening into the polder. Figure 4.52 shows how the tidal range is increased over time due the activation of TRM. It is the level of the ebb tide that controls the drainage ability of the beel/polder. From the plot it is seen that this improvement is achieved already in the second year of operation.

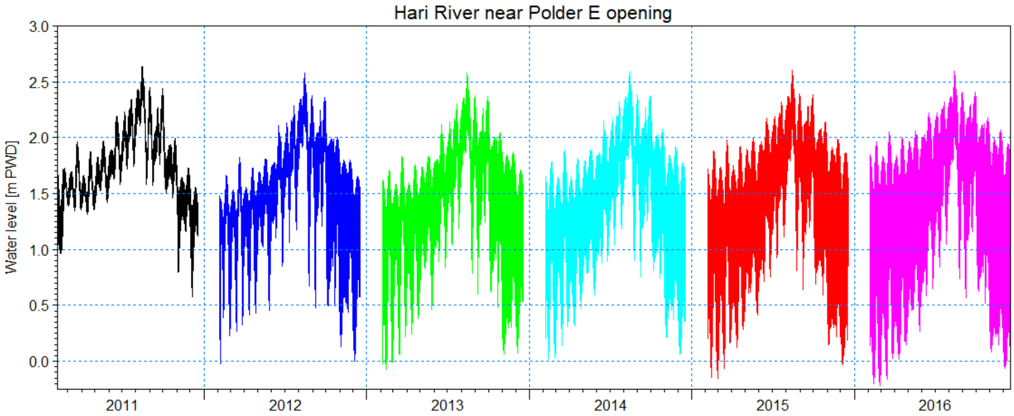

Figure 4.52 Tidal variation in Hari River near the polder opening after activation of TRM.

Figure 4.53 shows the initial bathymetry of the polder and the Hari River branch and the morphological development of bed levels the following six years after the opening into the eastern side of the polder. It is seen that the lack of side channels limits the deposition to areas along with the main channel being formed inside the polder and from Year 4 to 6 along with and inside the old main branch.

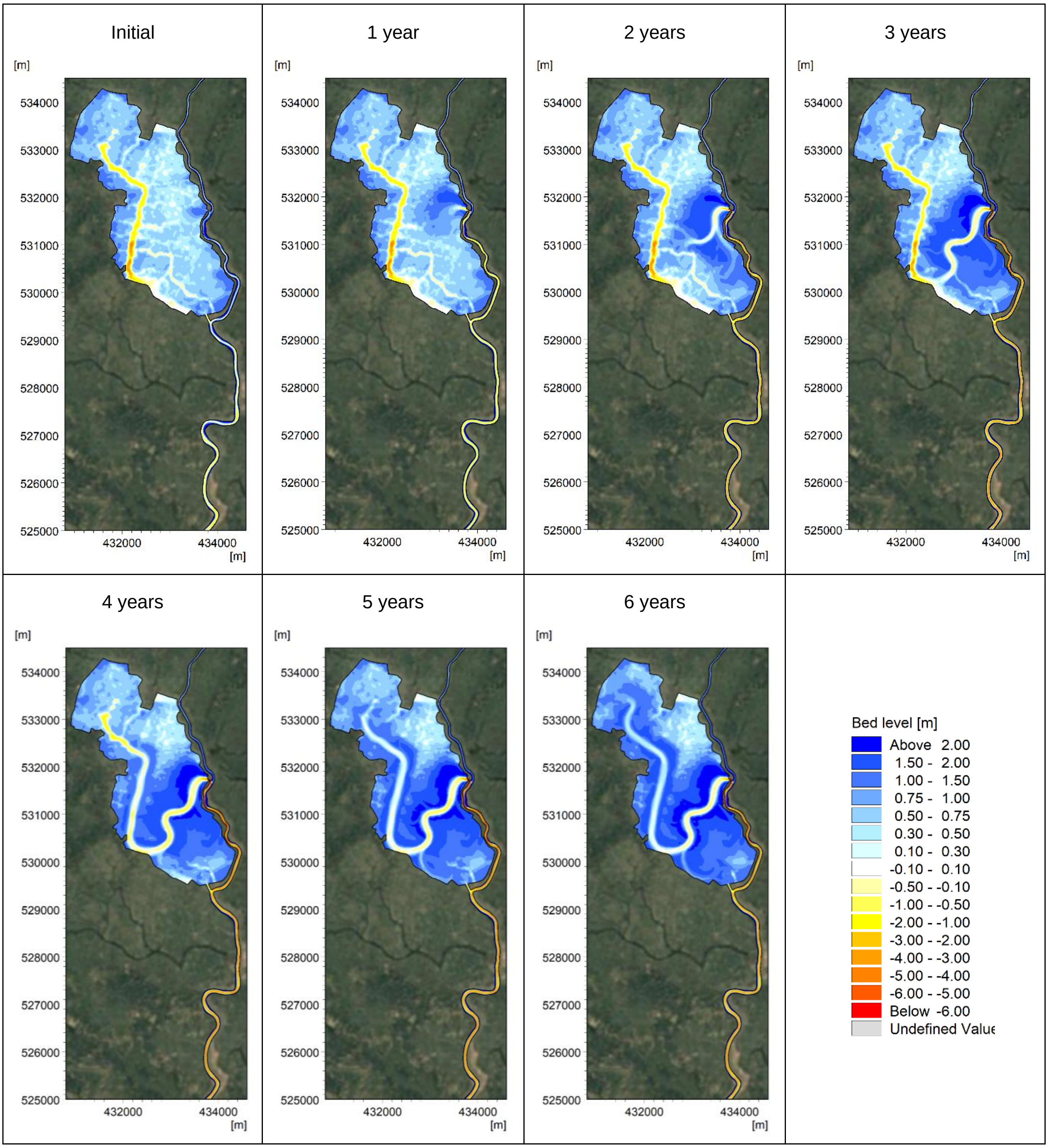

Figure 4.53 Bed level development after activation of TRM at the eastern side of the polder in the consecutive period of 6 years.

The corresponding plots showing the accumulated bed level changes are shown in Figure 4.54. From the plots, it is seen how the siltation pattern gradually migrate into the polder on the part of the low-lying floodplain next to the generated main channel inside the polder. When the generated main channel reaches the major channel in the old channel network from before the polders were established (Year 3 and 4) siltation is mainly taking place in the drainage network. The plots also show a gradual erosion taking place inside the Hari River branch downstream the opening into the polder. Erosion is also taking place in parts of the channel network inside the polder. This erosion is important to maintain the flushing ability of the polder and capability to penetrate water and sediment into the entire polder. However, the results show that the TRM is less feasible than the opening in the southern end.

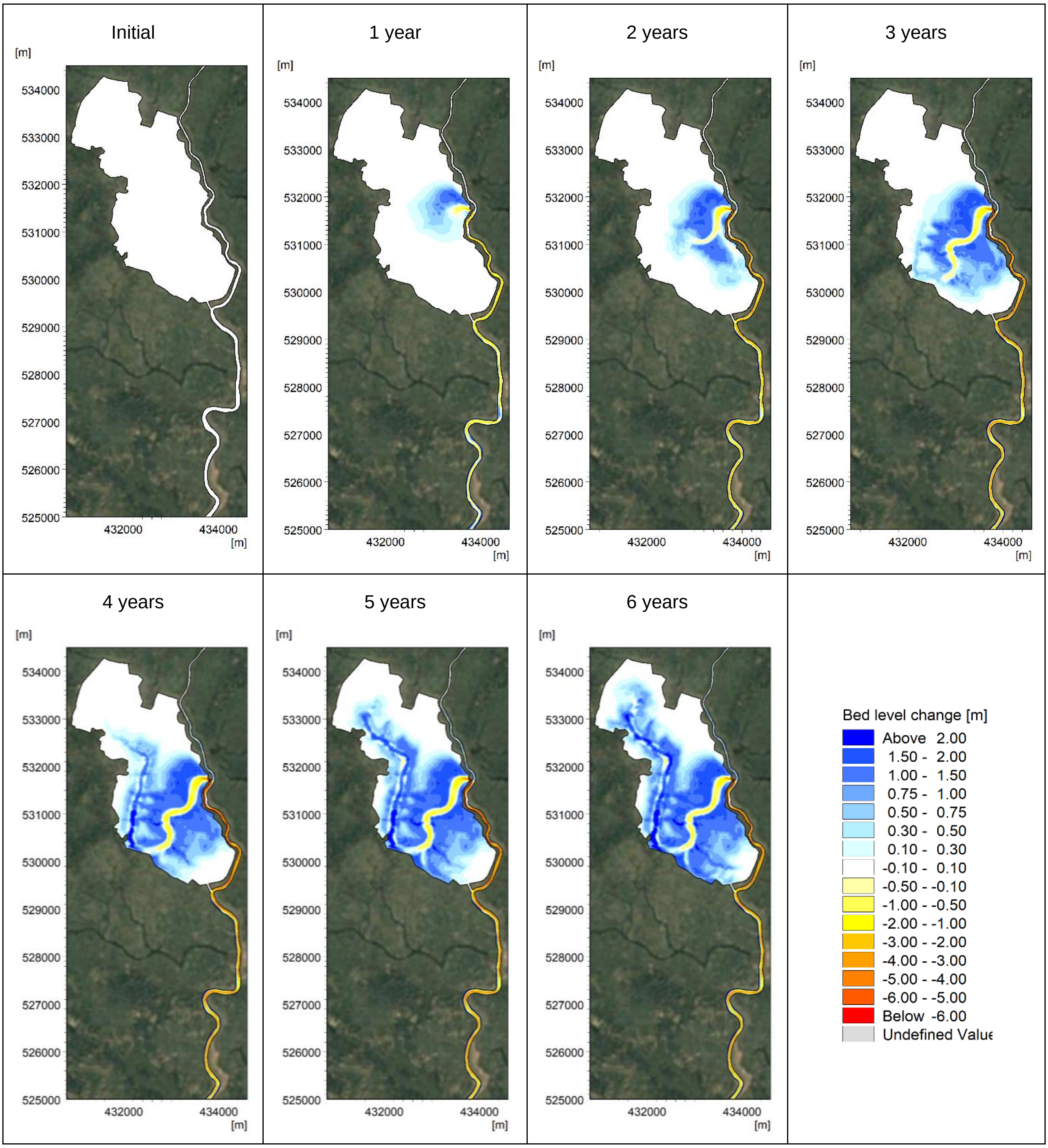

Figure 4.54 Bed level changes after activation of TRM at the eastern side of the polder in the consecutive period of 6 years.

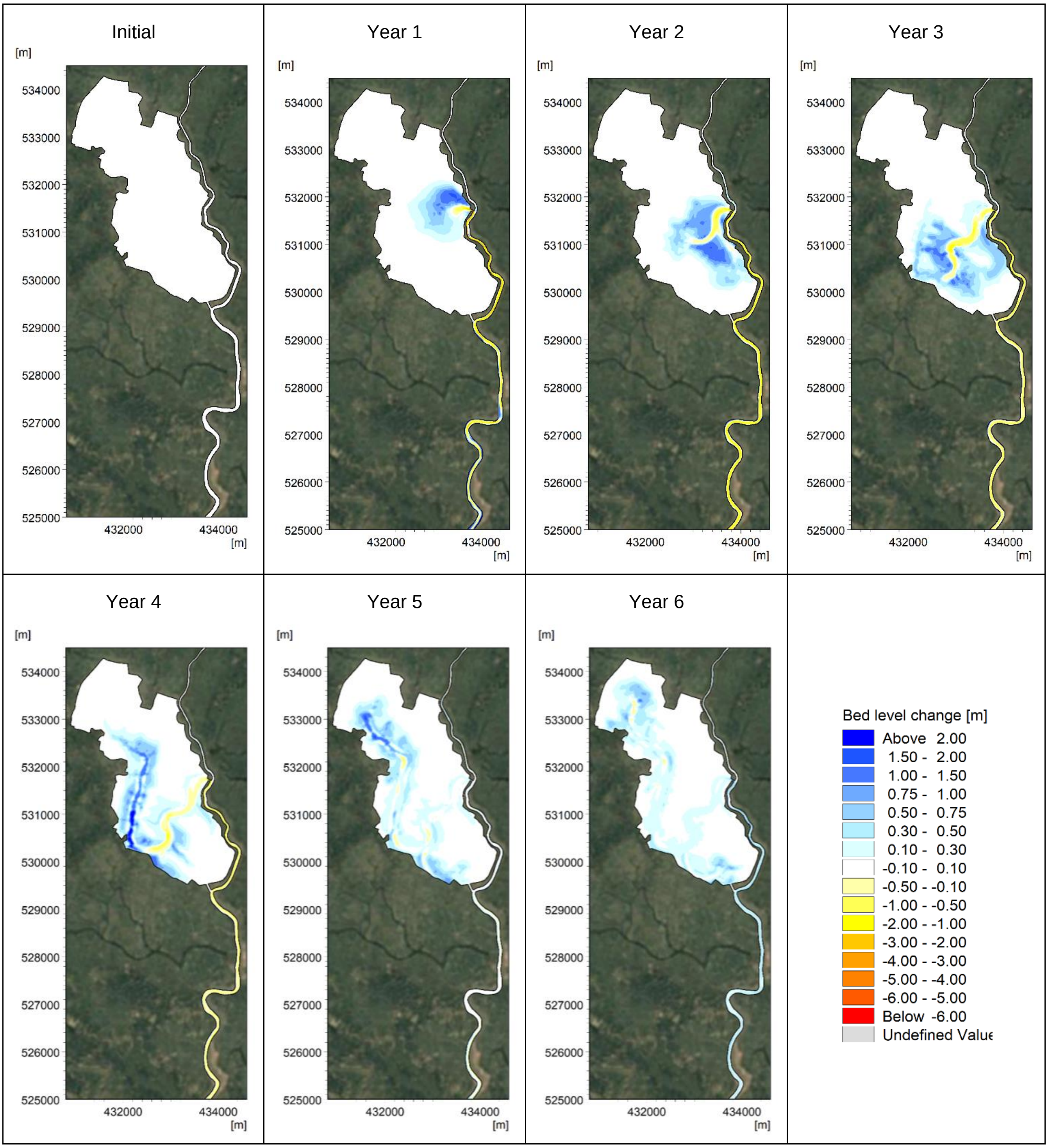

Figure 4.55 Annual bed level changes after activation of TRM at the eastern end of the polder in the consecutive 6 years.

Figure 4.55 shows the annual sedimentation and erosion inside the polder and the Hari River branch. It is seen that sediment is mainly settling in the area north of the eastern entrance channel during Year 1. In Year 2 deposition is migrating further inside and to the area south of the entrance channel, while at the same time the channel is eroding. In Year 3 the channel continues to erode and migrate towards south-southwest. Settling is mainly taking place in the southern part of the polder. In Year 4 the main channel continues to erode and migrate but reaches the old main channel. Deposition is mainly taking place in the old main channel and on the very nearby part of the floodplain. In Year 5 deposition is focused to the drainage network. In this year the Hari River branch reaches an equilibrium, i.e. erosion has stopped. Year 6 tendencies are similar with Year 5. The tidal volume of the polder is decreasing leading to siltation in the Hari River branch and the channel network inside the polder. The TRM has therefore lost its eligibility after 5 years.

TRM is seen to be an effective way to erode the part of the peripheral river located downstream the opening and thereby prevent water logging and drainage congestion inside the polders. The tricky part is related to optimising the deposition pattern inside the polder.

The temporal development of the upstream directed annual net sediment transport is shown in Figure 4.56 to Figure 4.59 for the cross sections at Ranai, Katakhali, Kanaishisa, and Polder E. It is seen that the largest net sediment transport is obtained for Year 5 at Ranai and Katakhali, and Year 4 at Kanaishisa and Polder E.

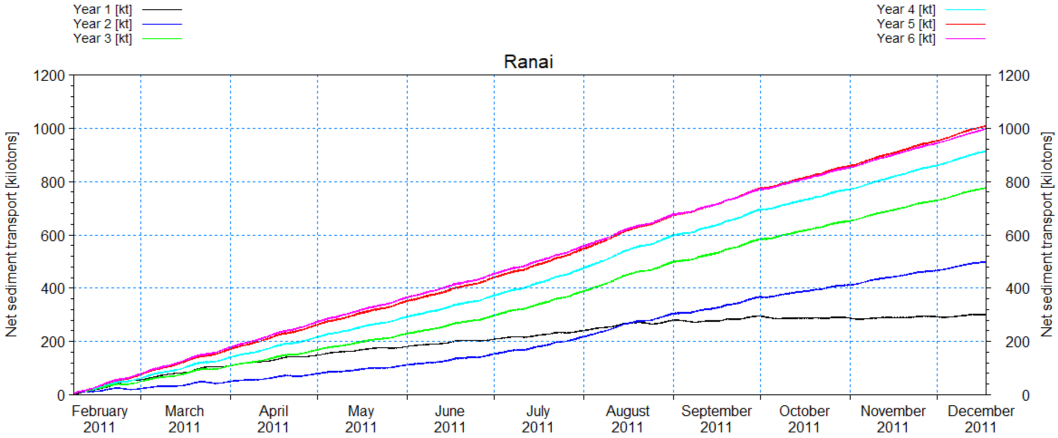

Figure 4.56 Net sediment transport at Ranai for each of the 6 consecutive years.

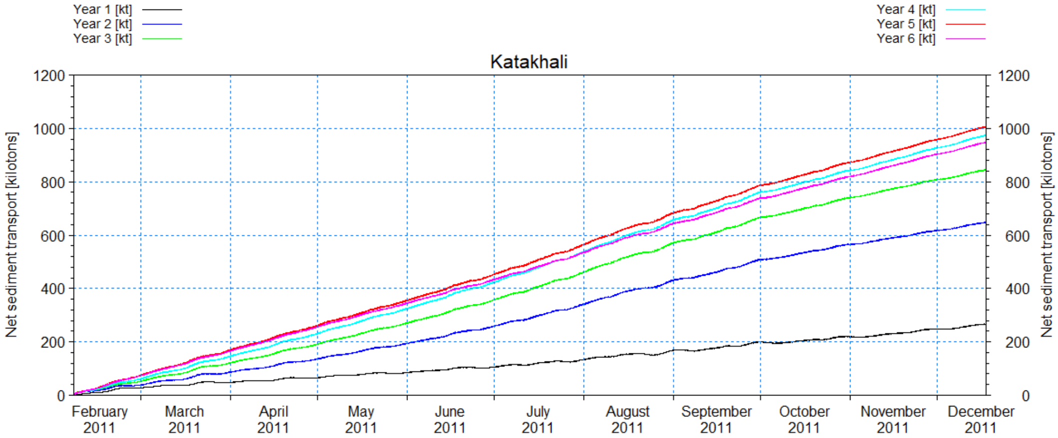

Figure 4.57 Net sediment transport at Katakhali for each of the 6 consecutive years.

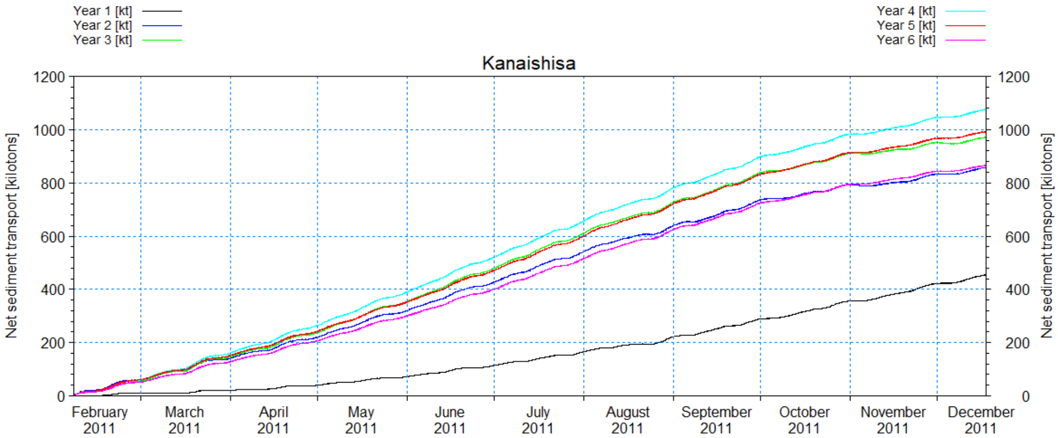

Figure 4.58 Net sediment transport at Kanaishisa for each of the 6 consecutive years.

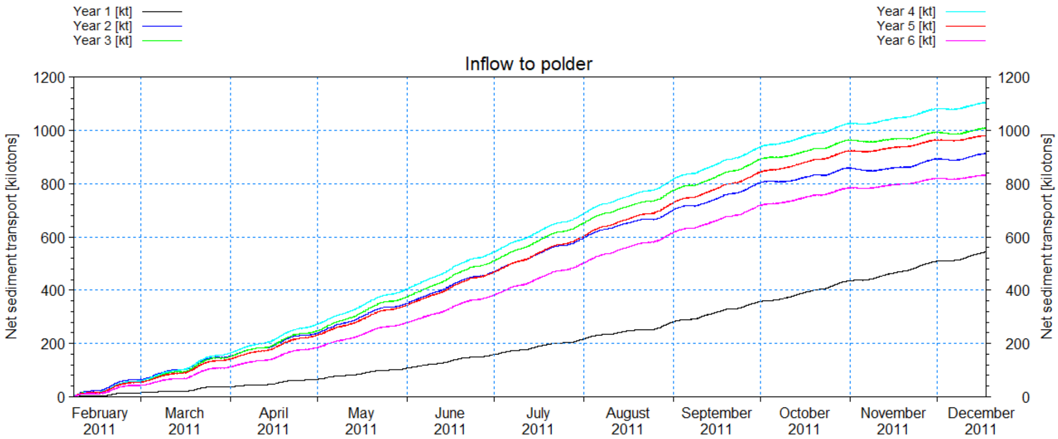

Figure 4.59 Net sediment transport at Polder E for each of the 6 consecutive years.

The calculated net sediment transport for each of the six cycles is listed in Table 4.7 for the cross sections at Ranai, Katakhali, Kanaishisa and Polder E. The net sediment transport at Kanaishisa is larger than the transport at Ranai and Katakhali in Year 1 to 4 due to the downstream migrating river erosion initiated by the opening to the polder and increased tidal prism. The beginning siltation of the river branch in Year 5 and 6 can also be revealed from the numbers in the table.

Table 4.7 Net sediment transport per cyclic period at Ranai, Katakhali, Kanaishisa, and Polder E.

Cyclic period	Ranai [kilotons]	Katakhali [kilotons]	Kanaishisa [kilotons]	Polder E [kilotons]
Year 1	301.4	266.7	454.3	543.2
Year 2	499.5	648.4	857.9	913.6
Year 3	776.6	844.6	971.1	1009.1
Year 4	915.0	974.5	1075.8	1104.7
Year 5	1009.3	1006.8	992.2	980.5
Year 6	997.1	948.3	865.2	832.1

The achieved impact obtained by use of TRM is illustrated in Figure 4.60. The diagram shows the area inside the polder, which is located above a given bed level value for initial bathymetry and the consecutive 6 years. It is seen that it is primarily the first 3 years the TRM is well-functioning. Siltation is also taking place inside the polder in Year 4-6, but this is mainly in the drainage network, which is of severe importance for the drainage ability of the polder after TRM operation has stopped. When comparing the diagram with the one shown in Figure 4.43, it is seen that the TRM efficiency is much less than what was obtained with the southern opening.

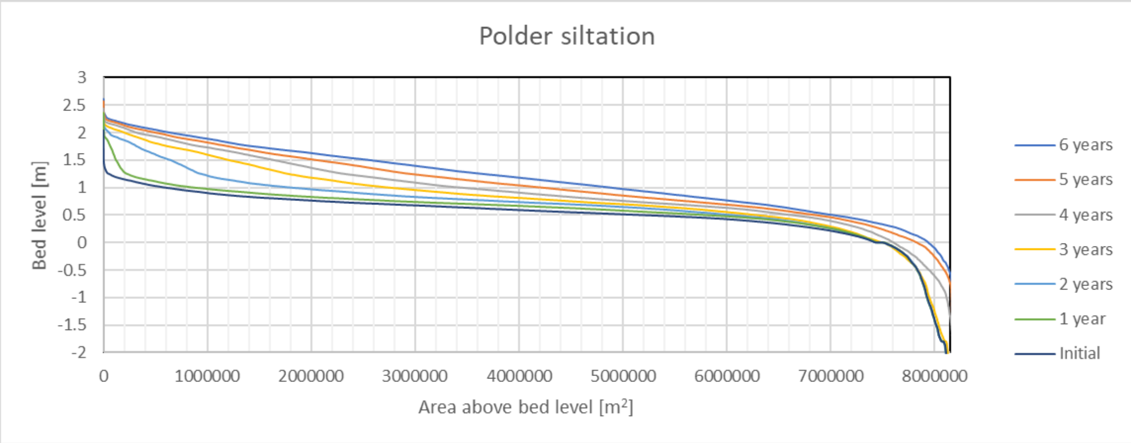

Figure 4.60 Area inside polder above a certain bed level during TRM operation.

A similar diagram (hypsometric curve) is made for the Hari River branch and shown in Figure 4.61, however in this case with focus on the deepest parts. It is seen that significant (but favourable) erosion takes place during the first three years. The erosion continues in the two following years, but with less pace. In year 6 sediment starts to settle in the river branch as the tidal prism of the polder decreases.

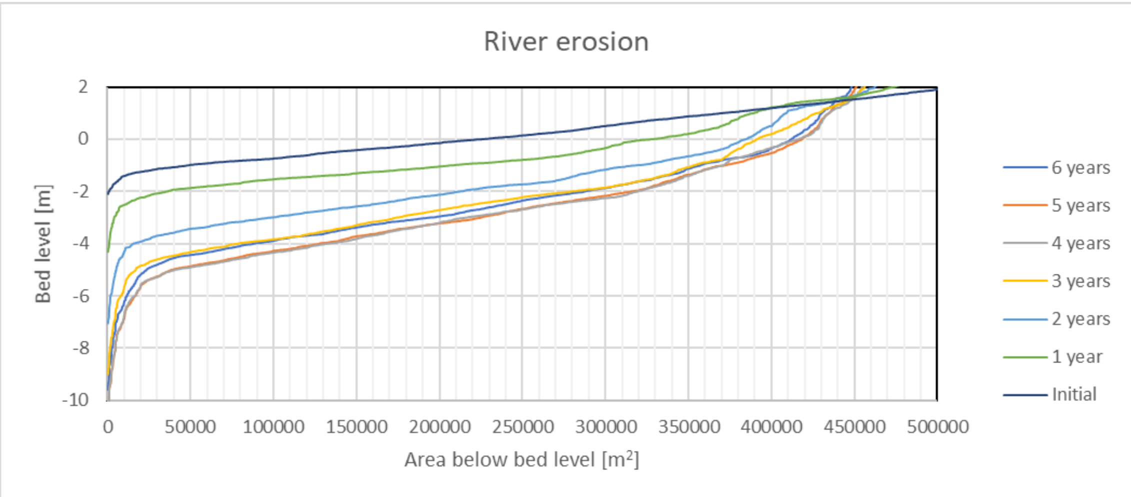

Figure 4.61 Area inside Hari River branch (downstream polder opening) below a certain bed level during TRM operation.

5 Conclusions, discussions, and recommendations

5.1 Conclusions and discussions

TRM has for many years been considered a viable way to maintain the drainage capacity of the peripheral rivers and for compensating the impact of subsidence by increasing land level inside the polders through deposition of silt. The key problem with TRM is that the area inside the polders, which are subjected to tidal flooding cannot be used for the intended purpose of the polders (viz. agriculture) while TRM is ongoing hence the population of the polders must be paid compensation and alternative livelihood created. An issue with TRM operation is also that deposition inside the polders is highly non-uniform. There is thus much to win if TRM operation can be optimised, i.e. accelerate erosion in the peripheral rivers, accelerated deposition within the polders and by ensuring a more uniform deposition pattern. The objective of TRM modelling is to establish a modelling approach that can be used to test alternative TRM operations and help identifying the most effective operations.

The purpose of modelling presented in this interim report is to explore what will be required in terms of modelling to optimise TRM operation and is based on the application of a very simple 1D modelling approach and a state-of-the art 2D modelling approach. The models simulate the hydrodynamics and advection-dispersion of suspended sediment represented by one (representative) size fraction only. Erosion and deposition are as sources and sinks in the advection-dispersion model and calculated as simple/standard functions of the cross-sectional average bed shear stress (1D) and spatially resolved in the 2D approach (thus a standard cohesive sediment modelling approach).

The TRM operation implemented for East Beel Khuksia has been used as pilot case because this is the best described and most successful TRM operation. Furthermore, it contains accessible information and data. The Beel and River system of the area is shown in Figure 1.4. Tidal River Management had been adopted since 1998 in the north-west part of the Khulna Jessore Drainage Rehabilitation Project to solve drainage congestion. Beel Bhaina and Beel Kedaria (see Figure 1.4 for location of these polders) were subjected to tidal flooding and created sufficient tidal volume to maintain the drainage capacity of Teka and Hari Rivers. During the dry season of 2005 TRM operation of Beel Kedaria ceased and the Hari river was rapidly silting up. A rough estimate suggested that 800,000 tons of silt was deposited during a period of three months.

In response to the lost drainage capacity of the Hari River TRM operation was initiated at the East Beel Khuksia on 30 November 2006. Ahead of the opening of the TRM basin about 0.8 x 10^6 m^3 was dredged from the peripheral Hari River along a reach of approximately 8 km to amplify the tide. Before the opening of the TRM basin the tidal volume of the Hari River was about 0.9 x 10^6 m^3 but increased to 1.95 x 10^6 m^3 after two months of operation and 5.3 x 10^6 m^3 after 5.5 months. A major part of the tidal volume increase was caused by flushing of the peripheral rivers that at Rania was deepened by more than 2 meters. A minor part of the tidal volume increase is related to seasonal variations of the tide, which typical has the largest range in the months of March and April. Significant erosion took place in the peripheral rivers and an estimated 1.2 mill tons of silt was deposited within the polder.

1D model

A curtailed version of the SWRM was used in this study for the 1D modelling and to provide boundary conditions for the 2D model. The MIKE 11 model was used for simulation of the siltation after TRM operation of Beel Kedaria ceased and for the erosion of peripheral rivers and siltation within Beel Khuksia when TRM operation commenced. Booth of these events took place during the dry season. No model boundary conditions were available for the period 2005 through 2007. Instead, a period from January to April 2011 was used. Despite of this, the agreement between model and observations were surprisingly good. Water level variations during spring tide compared well with the observed variation. During neap tide the simulated low waters became lower. This behaviour was not found in the observations, suggesting that bed elevations in the model was too low. The application of a morphological model (with update of bed elevations due to erosion and deposition) would probably improve this.

Simulated and observed sediment concentrations compared remarkably well in the Hari River when the tidal range is well predicted by the HD model (1D). The (calibrated) sediment parameter values used are all quite similar to those used in other model studies in Bangladesh and elsewhere. Inside the polder the agreement is less. Here it also seems that the measurements are less accurate. In the model the concentration during ebb flow is zero (suggesting that all sediment entering the East Beel Khuksia will deposit). Sediment and water will enter the polder via the drainage canals and deposition first take place when the water spills into the polder. This discrepancy thus suggests that a 2D description is required to correctly represent the conditions within the polders. Another contributing explanation could be that part of the finer sediment fractions will remain in suspension inside the polder because of the low settling velocity, whereas the observed concentration may be larger than zero. A multi-fraction approach may render better agreement with the observations. 2D modelling of the East Beel Khuksia would also improve the model performance.

The simulation shows a strong asymmetry (between flood and ebb flow) in sediment transport leading to a significant net transport of some 400,000 tons into the Hari River. This should be compared with the net accumulation of 800,000 tons estimated from observed cross-sections for a similar period.

Simulation of TRM operation of the East Beel Khuksia shows that about 200,000 tons of sediment erodes from the riverbed and some 400,000 tons of sediment enters the Hari River from downstream. The sediment eroded from the riverbed plus the net sediment transport into Hari River ends up in the East Beel Khuksia, where thus close to 600,000 tons deposit. For a period of four months, we have calculated the deposited volume to 1.2 mill tons (an uncertain estimate, see Section 2.3), thus the model predicts the right order of magnitude.

2D-model

A conceptual state-of-the-art 2D model was developed to simulate the gradual siltation of Hari River caused by the tidal asymmetry and modest runoff from the catchment, which thereby creates a net upstream directed sediment transport. Even though the applied HD boundary was based on a channel bathymetry from a different period (2015) the model was able to simulate a gradual siltation of the branch. The siltation time scales depend strongly on the sediment concentration specified as boundary condition on the downstream boundary, but that makes it on the other hand easy to adjust the siltation rates if/when calibration/validation data becomes available. For the modelling a constant sediment concentration was applied. In a detailed study it would be possible to refine the boundary condition introducing a neap-spring variation and/or a seasonal variation. However, this does not make much sense to do so with the present data basis.

The Hari River model was extended to include the East Beel Khuksia located inside Polder 24 and openings at the southern end and at the eastern side. Openings that have been used for the TRM operation of the beel. The Hari River bathymetry was established from measured cross sections in 2015 and do thereby not represent the branch at the time when TRM was initiated. The modelling carried out is thereby only conceptual but represents a morphological time scale of almost 6 years.

Two TRM scenarios were investigated. One with an opening in the southern end of the polder and one with an opening in the eastern end of the polder. The modelling with a southern opening revealed a strong potential for TRM, while the modelling with an eastern opening showed less potential. In both cases the TRM had a significant improving impact on flushing the part of the peripheral river located downstream the polder opening. The concept is thereby found feasible for this purpose.

With regard of the purpose of siltation and increase of bed levels inside the polder number of lessons was learned. Placing the polder opening as far as downstream as possible compared to the beel will ensure the largest tidal discharge and largest tidal envelope. This is important ensure a strong interaction with the beel. By placing the entrance channel, so that it becomes connected with the old channel network from before the polder was established, it can be better ensured that the siltation will takes in a larger part of the beel. The TRM system with an opening in the south contains a network with several side channels which stimulate a more evenly distribution of the imported sediment. This was not the case for the TRM system with an opening in the eastern side of the beel. This system had mainly a main channel along which the sediment deposited. The eastern opening was located in an area of the polder with a relatively high bed level and no presence of an existing channel network, i.e. incoming water had to erode its own channel. This is not optimal with regard of getting a more uniform distribution of the imported sediment inside the polder and a large tidal prism. A better TRM efficiency can thereby be achieved by pre-dredging an internal channel inside the polder that ensures good connectivity with the existing channel network inside the polder.

5.2 Recommendations

Before activating the TRM operation in November 2006 about 0.8 x 10^6 m^3 was dredged from the peripheral Hari River along a reach of approximately 8 km to amplify the tide. Dredging was not required to achieve a significant exchange with the beel in the simulations. The main reason for this is most likely that the Hari River branch in the model is deeper along the reach from the eastern polder opening and down to the old polder opening at Beel Bhaina. It could be interesting to use the morphological model for the Hari River to establish a branch, which represent a system with an initial river bathymetry that better corresponds to the conditions back in November 2006 before activating TRM. Another option could be to test a model based on two sediment fractions. This is however a quite complex task because the sediment entering the polder is eroded from the riverbed. To do so one will need to know how the composition of the two fractions is distributed.

6 References

/1/ IWM, March 2006: Monitoring the performance of Beel Kedaria TRM and baseline study for Beel Khuksia. Khulna Jessore Drainage Rehabilitation Project. Final Report.

/2/ IWM, July 2007: Monitoring the Effect of East Beel Khuksia TRM Basin and Dredging of Hari River for Drainage Improvement of Bhabodah Area. Khulna Jessore Drainage Rehabilitation Project. Final Report.