Blue Gold Program

The Study of River Bank Erosion Management in Polder 29, Khulna

Final Report

April 2016

EXECUTIVE SUMMARY

E1 Introduction

Bangladesh is a riverine country and the rivers carry huge water and sediment discharge during monsoon. In the dry season, the coastal rivers carry huge sediment with saline water during high tide from the Bay of Bengal. Riverbank erosion, sedimentation and salinity are the major devastating events of the south-west region of Bangladesh. River bank erosion mainly occurs due to displacement and transportation of non-cohesive bed material caused by excessive flow and non-resistant velocity resulting to shift the thalweg and widening the top width of the river. Every year nearly one million people are affected by bank erosion. River bank erosion causes loss of land, displacement of human population and livestock, disruption of production, evacuation and loss of property.

Polder 29 has been experiencing bank erosion problem for a long time and the embankment was retired several times due to severe erosion of the Lower-Bhadra river. Since the last several years right bank of the Bhadra river is eroding at Chadgar and Baroaria Bazar in the Upazilla Dumuria. Local community has lost their productive land and homesteads due to erosion. They approached to different authorities for protective measures. IWM was entrusted by Blue Gold on 19th February 2015 for the study of "River Bank Erosion Management in polder 29, Khulna" to identify causes of erosion and develop a comprehensive and innovative adaptive approach for mitigating erosion. This report contains description of the prevailing problems, data collection and analysis, model development, morphological behavior of the study area, mitigation measures for bank erosion, design and costing of mitigation measures.

E2 Data and Model

A comprehensive attempt was made for the collection of field data of tide, water flow, river cross-section, sediment sample and satellite image and secondary data from different sources at key locations along the peripheral rivers of the polders to understand the tidal and sediment characteristics of these rivers. Hydrodynamic modelling has been carried out for determination of erosion prone stretch of the river bank and assessing effectiveness of erosion mitigation measures. The field survey campaign was carried out at two phases: during dry season (April ~ May, 2015) and during Monsoon (July ~ August, 2015) to collect the data on river cross-section, water level, water flow, velocity, river bed materials and suspended sediment concentration. These data have been utilized to establish baseline hydrodynamic and morphological conditions, to identify critical erosion prone areas, to identify causes of erosion and potential mitigation measures and also for development of the model.

The hydrodynamic model has been calibrated and validated against water levels and discharges. Simulations were carried out for dry and monsoon period to establish base condition, existing flow distribution, current field, erosion prone area, suitable bank protective measures, effectiveness of protective works, and design parameters for designing protective work.

E3. Accretion and Erosion Rate

Significant riverbank erosion is observed along this polder. Available satellite imageries of 2001, 2009, 2011 and 2015 were analyzed in order to estimate the erosion rate. The erosion/accretion was calculated at every 200 m interval along the chainage of peripheral embankment of the polder 29.

Satellite image analysis shows that erosion is dominant along the right bank of Lower Bhadra river from 2001-2009. Nearly 20.81 ha land was eroded away along the right bank of Lower Bhadra river from 2001-2009. Total length of the eroding bank is about 3.90 km. On the other hand, huge accretion was occurred during this period along the left Bank. Approximately 66.20 ha of land was accreted within 2.68 km river reach. Actually during this period (2001-2009) the river changed it course. Near Jaliakhali, there was a bend which became straight during this period.

Erosion is also prominent during the period 2009-2015 along the right bank. Total eroded area and length along right bank are 19.14 ha and 4.81 km respectively. In addition to this, accretion also occurred along the right bank. Total accreted length and area adjacent to river bank is about 1.08 km and 5.55 ha respectively. On the other hand, along left bank huge accretion was occurred. It is clear from the image analysis that the river shifted towards west over the period.

E4 Erosion vulnerable area and Extent of Bank Protection Works

The criteria for selecting erosion vulnerable area are:

- Near bank velocity
- Angle of attack
- Distance of thalweg line (deeper channel) from bankline
- Locations of deep scour holes
- River bank slope

The vulnerable locations of the project are considered at locations of deep scour hole, where the bank slope is steep. Position of thalweg line (deeper channel) is also considered to be an important indicator in identifying location of potential bank erosion. When thalweg line approaches very closer to the bank line, the location or bank-line is very susceptible to erosion. It is observed that the deep channel gradually shifting closer to the right bank as because scour depth was gradually increasing near the erosion vulnerable area. The thalweg line is shifted towards the right bank over the period and maximum thalweg line shifted from 2007 to 2015 is about 207 m. It is seen that the deep channel has approached very close to the bankline near Chadgar, Jaliakhali and Baroaria. It indicates that these portion are in the active process of very severe bank erosion. It is seen that a stretch of 1.63 km length of bankline near Chadgar and 1.45 km length of bankline near Baroaria are vulnerable to bank erosion. These areas need bank protection. The locations are shown in Figure E-1.Although satellite images analysis from 2011-2015 show that bank erosion is continuing along the bank from Jaliakhali to the east of Baroaria, erosion protection measures have not suggested here as because sufficient setback distance is remaining here from bankline to embankment. This portion is in dynamic equilibrium condition. Satellite image analysis from 2009-2011 shows a huge accretion here but erosion started from 2011-2015. Ultimately from 2009-2015 this area experienced net accretion. At present erosion protection measure have not been suggested here but close monitoring of bankline is necessary which is recommended for future action.

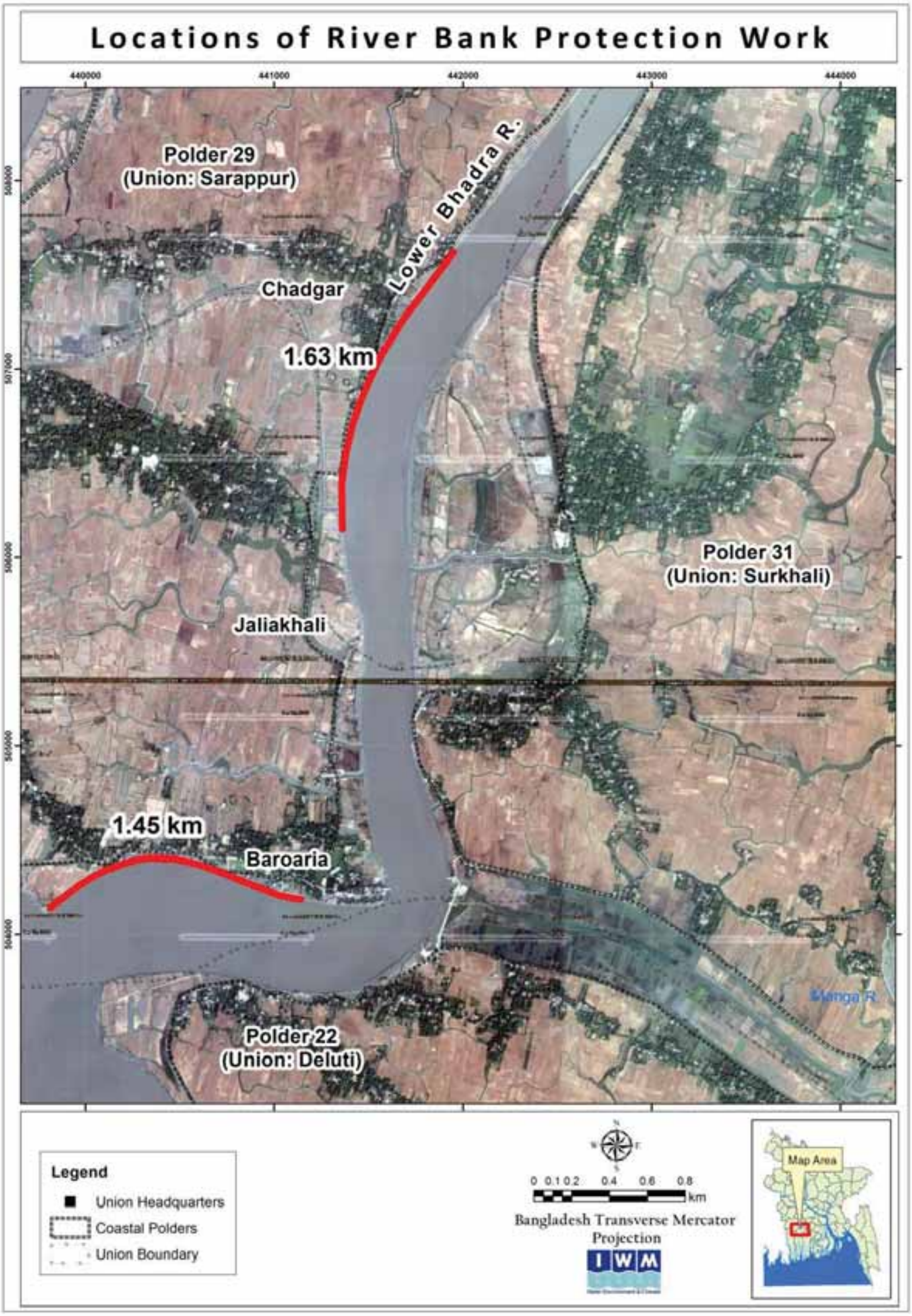

Figure E-1: Proposed bank protection locations

E5 Selection of mitigation measures and costing of different alternatives

Selection of alternative mitigation measures and final selection of bank protection measure needs to be cost-effective, sustainable against likely changed flow regime and morphological behaviour and acceptable from technical, environmental and social consideration. The following alternative measures have been investigated for river bank protection of the study area for selecting best suitable measures.

- Bottom Vane:
- Porcupine:
- Bamboo Bandalling
- Permeable Spur/Groyne

These measures have been analyzed and permeable spur has been selected as recommended option. The effectiveness of permeable spur has been assessed by simulation of flow condition for different hydrological conditiont. River hydraulic condition has been simulated in dry and monsoon period considering the permeable spurs. The results showed positive response in the erosion reduction process with permeable spurs. Reduction of current speed and sediment deposition along the erosion vulnerable area are evident.

For cost analysis, three different bank protection measures have considered for bank protection measures. The considered options are

Option-1:Semi-permeable spur from riverbank up to scour hole + sand-filled Geo-bag dumping at scour hole.

Option-2: Slope protection with CC block + Geo-bag dumping at scour hole.

Option-3:Semi-permeable spur from river bank up to scour hole.

The estimated cost has also been used for selection of the most appropriate option. The cost estimate of proposed protection works is prepared on the basis of estimated quantity from prepared drawings and rates taken from current "Standard Schedule of Rates Manual, Volume II; Item and Element Rates" of Feni O & M Circle, BWDB, Feni effective for the year 2014-2015.

The total estimated cost for option-1 is Tk 49.00 million, for option -2 Tk 243 million and for option-3 it is Tk 23.00 million.

E6 Final selection of mitigation measures for bank protection work

Option -1 has been selected the best suited option for mitigation measures considering effectiveness, costing and social acceptability.

Based on the model result analysis, series of top blocked semi-permeable spurs/groynes (1.5 m from the top of the semi-permeable spur) making an angle 60^0 to the bankline is the most suitable for bank protection measure and has been recommended as erosion mitigation measure. Top blocked semi-permeable spur has been considered along 1.63 km length near Chadgar and 1.45 km near Baroaria along the right bank of Lower Bhadra river. Protrusion length of the semi-permeable spur determined by distance between river bank to the local scour hole. The reason to limit the protrusion length up to the scour hole is to minimize the length of spur pile. For example, elongation of a typical spur place at -12 mPWD (Figure 5-3) is 20 meter. Here, length of a wooden pile is 15 meter [(12+3) meter]. Hence for 5 meter embedment, 20 meter wooden pile is required. Construction of 20 meter wooden pile is difficult in the field. Local scour hole beyond the groyne system is filled with sand filled geo-bag. The level of geo-bag filling is adjusted from the bathymetric survey to minimize the bank erosion and to reduce the vulnerability of furthest pile in a spur system. Maximum protrusion length is limited by 50 meter. The protrusion length of each spur varies from 25-50 m at Chadgar and 20 – 50 m at Baroaria. The spacing of permeable spur along the river is 2.5L, where L is the protrusion length of the permeable spur. Spacing varies based on the protrusion length of the permeable spur. The spacing of the semi-permeable spurs varies from 65-125 m in Chadgar and 70-140 m in Baroaria. In order to avoid or minimize the scouring around the bottom of the wooden pile, dumping of brick bats is suggested.

The semi-permeable spur is designed by full blockage of 1.5 m from top. The remaining part of the spur has 40-50% blockage and 60-50% open. Top blockage can be made with Galvanized Iron (GI) Sheet. The permeable spur would be constructed by wooden piles. The diameter of each wooden pile is 0.2 m. It is recommended to tie the whole length of the permeable spur by a pair of horizontal wooden piles perpendicular to the bank line. Each of the two horizontal “tie piles” should be fixed firmly with the vertical member of a spur with G.I nut-bolts /screws through a hole drilled at the crossing of the horizontal and the vertical wooden piles of a spur) to act as a monolithic member.

E7 Implementation of mitigation measures as pilot basis

It is decided to assess the effectiveness of the proposed mitigation measures as a pilot basis before implementation for whole erosion vulnerable area. Primarily six permeable spurs have been considered along the right bank of the Lower Bhadra river which covers approximately 500 m of erosion vulnerable river bank. Total cost for implementation of the mitigation measure as pilot basis along 500 m river bank is BDT 7 million.

E8 Construction and Monitoring

It is not reasonably possible to develop structures that are maintenance free. In terms of maintenance and operation it will need some special care or manual to maintain the blockage ratio. Maximum blockage should not exceed 50%.One of the reasons for providing maximum blockage of 50% may be that, it will be difficult to make the structure (made by the local materials like wooden log or bamboo etc.) safe against the impact of monsoon flow with more blockage. Blockage can be made by Galvanized Iron (GI) Sheet. Local erosion around the structures it needs periodic monitoring and maintenance. As local scour around the structure is much less than impermeable spur, maintenance of permeable spurs is the least compared to other structures.

The proposed bank protective works need to be monitored and subsequently maintenance of the same shall be undertaken on regular basis. Effectiveness of bank protection measure largely depends on proper monitoring .Monitoring is a process that provides information and ensures the use of such information to assess the project effects. It helps to enhance the performance and achieve desired results of any bank protection measures by improving the current and future plan for maintenance and other things. The data and information generated by the monitoring system is a way of analyzing present performance and future work plan.

The monitoring consists of following activities:

1. Identification of abnormal scour hole at different parts of permeable spur including upstream and downstream terminations through hydrographic survey before and after monsoon.
2. Assessment of sedimentation along the protective area and bank erosion or not
3. Assessment of bank line shifting at upstream and downstream of permeable spur by land survey once in a year.
4. Visual inspection of works that are above low water levels.
5. Measurement of current speed during monsoon.

In view of above, it is recommended to adopt following measures considering monitoring and maintenance activities:

- Routine visual inspection of permeable spur/spur;
- Keeping the blockage at least 40%;
- Survey of sections at suitable interval before, during and after monsoon;
- Survey of bank line shifting at upstream and downstream of spur;
- Keeping annual maintenance cost including and
- Immediate repair of any damage of spur to avoid major rehabilitation.

E9 Recommendations

I. It is recommended to protect the total 3.08 km erosion vulnerable river bank along the right bank of Lower Bhadra river by series of semi-permeable spur with sand filled Geobag dumping (option-1). The top of semi-permeable spur will be blocked by Galvanized Iron (GI) sheet. The semi-permeable spur is designed by full blockage of 1.5 m from top and the spur has 50-60% permeability at the bottom. The protrusion length of the spur is upto scour hole. Maximum protrusion length is around 50 m. The spacing of the spur along the bank is 2.5L (L= Protrusion length). In order to avoid or minimize scouring around the bottom of the wooden pile, brick bats are recommended. A pair of horizontal wooden piles is recommended to tie all vertical members of a permeable spur along the whole length.

II. The proposed bank protective works need to be monitored to generate data, information, new knowledge and to take corrective measures in time.

III. Before Implementation of the erosion mitigation measures as whole, it is recommended to implement on a pilot basis for monitoring the effectiveness this work and to review and make necessary correction/modification if necessary in the design /implementation process.

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ACRONYMS AND ABBREVIATIONS

ADCP		Acoustic Doppler Current Profiler
BM	-	Bench Mark
BWDB	-	Bangladesh Water Development Board
DAE	-	Department of Agricultural Extension
DHI	-	Denmark Hydraulic Institute
DRR	-	disaster risk reduction
FM	-	Flexible Mesh
GIS	-	Geographic Information System
IWM	-	Institute of Water Modelling
RTK-GPS	-	Real Time Kinematic Global Positioning System
SWAIWRMP		Southwest Area Integrated Water Resources Management Project
SWMC	-	Surface Water Modelling Centre
SWRM	-	South West Regional Model
TBP	-	Top Block Semi-Permeable Spur
USGS	-	United States Geological Survey

1 INTRODUCTION

1.1 Background

Bangladesh is a riverine country and the rivers carry huge water and sediment discharge during monsoon. In the dry season, the coastal rivers carry huge sediment with saline water during high tide from the Bay of Bengal. Riverbank erosion, sedimentation and salinity are the major devastating events of the south-west region of Bangladesh. River bank erosion mainly occurs due to displacement and transportation of non-cohesive bed material caused by excessive flow and non-resistant velocity resulting to shift the thalweg and widening the top width of the river. Every year nearly one million people are affected by bank erosion. River bank erosion causes loss of land, displacement of human population and livestock, disruption of production, evacuation and loss of property.

Blue Gold is a collaboration program between the Government of the Netherlands (donor) and the Government of Bangladesh. The program is implemented by the Ministry of Water Resources, through Bangladesh Water Development Board (BWDB, lead agency) and the Department of Agricultural Extension (DAE). The Blue Gold project was launched on 20 February 2013 and will end on 19 February 2019.The overall objective of the project is to reduce poverty for 150,000 households living in 160,000 ha area of selected coastal polders in Khulna, Satkhira and Patuakhali by creating a healthy living environment and a sustainable socio-economic development. The main activities of Blue Gold Programme are:

- Community Mobilization and Institutional Strengthening;
- Water Resources Management;
- Agricultural Production;
- Business development and private sector involvement and
- Cross-cutting issues like training and capacity building, gender, monitoring and evaluation, environment, disaster risk reduction (DRR), good governance etc.

Polder 29 has been experiencing bank erosion problem for long time and the embankment was retired several times due to severe erosion of the Lower-Bhadra river. Since the last several years right bank of the Bhadra river is eroding at Chadgar and Baroaria Bazar in the Upazilla Dumuria. Local community has lost their productive land and homesteads due to erosion. They approached to different authorities for protective measures. IWM was entrusted by Blue Gold on 19th February 2015 for the study of "River Bank Erosion Management in polder 29, Khulna" to identify causes of erosion and develop a comprehensive and innovative adaptive approach for mitigating erosion. This report contains description of the prevailing problems, data collection and analysis, model development, morphological behavior of the study area, mitigation measures for bank erosion, design and costing of mitigation measures.

1.2 Objectives

The objectives of the study are:

- To identify the underlying causes of river erosion
- To find the extent of erosion in order to control erosion by providing mitigation and protective measures
- To develop a comprehensive, ecologically sustainable and innovative adaptive approach for the planning, design and implementation of the erosion protection work in the proposed site.

1.3 Scope of Works

The main scopes of services are as follows:

- Compilation and analysis of existing data;
- Recent hydrometric data collection from secondary sources;
- Bathymetric survey in the Shalta, Bhadra and Gangreil river to devise the mitigation measures by analyzing the data and for model development;
- Water level , flow, suspended sediment concentration and bed material measurement and analysis;
- Time series satellite image analysis for identification of bank-line shifting characteristics, previous erosion rate and to predict future probable erosion pattern
- Identify critical locations of probable bank erosion (present and future) supported by numerical model and data analysis;
- Devising mitigation and corrective measures as appropriate, and select most appropriate innovative approach
- Developing comprehensive design parameters and prepare detailed design for the bank protection work and other allied works;
- Cost analysis

1.4 Output of the Study

- Flow condition of the peripheral rivers of polder 29
- Erosion/deposition pattern based on model results and data analysis and erosion vulnerable area;
- Critical location for erosion;
- Most appropriate approach for erosion protection;
- Comprehensive design parameters on the basis of the developed, updated, calibrated, validated and simulated model results;
- Detailed design of River bank protection work and allied works
- Cost estimate of protective work
- Recommendation of the monitoring and maintenance needs (strengthening) on the basis of response analysis

2 PHYSICAL SETTING

2.1 Study Area

The study area is situated in the south-west region of Bangladesh within the upazila Dumuria & Batiaghata under the district of Khulna and the polder is surrounded by Lower Shalta (north and east), Lower Bhadra (east and south) and Gangreil (west) river. The total embankment length of the polder is about 49 km and gross protected area is about 8,218 ha. The cultivable land is about 6,570 ha and total length of the drainage channel is about 39.5km. The existing crest level of the embankment is 4.27 m PWD.

Bhadra river has been eroding the river bank along the river stretches near Chadgar and near Baroaria Bazar, eventually the embankment and other social structure have become vulnerable to erosion. Satellite image analysis shows that about 20.16 ha land was eroded away from 2009 to 2015. It causes huge suffering and property losses of the local people. Proper mitigation measures should be taken to stop the erosion process. Traditional approach of bank protection work such as revetment, groyne are costly and not environment friendly. Innovative approach with low cost method will have to be applied for diminishing the existing the erosion problem.

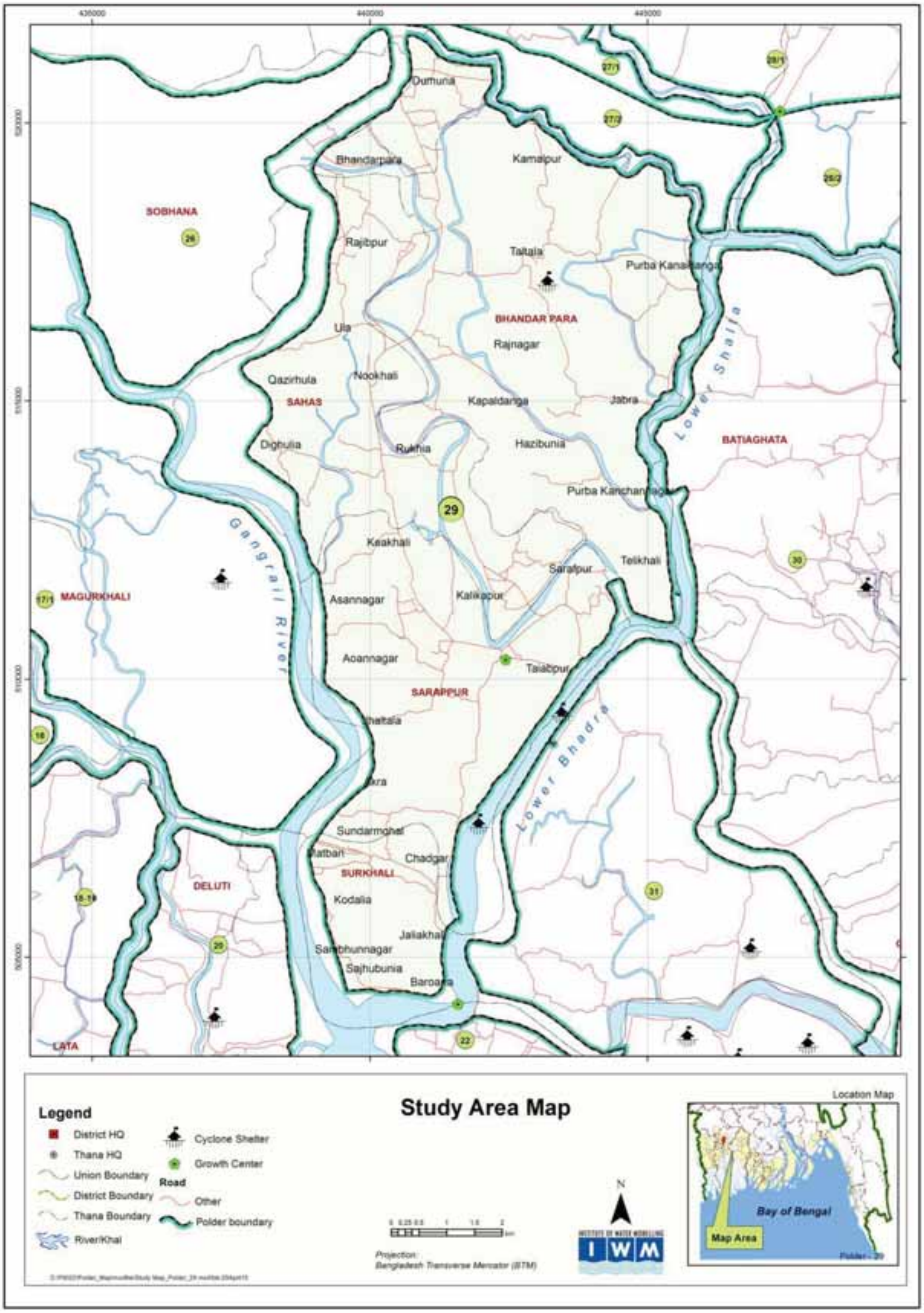

Figure 2-1: Study area map

2.2 Climate

The Study area has a typical monsoon climate with warm and dry season from March to May followed by a rainy season from June to October and cool period from November to February. In winter, there is much less rainfall than in summer. According to Köppen and Geiger, this climate is classified as Aw. The mean annual rainfall (sum of average rainfall of each month) in the area is 1711 mm of which approximately 70 % occurs during the monsoon season. Potential evapo-transpiration rates are of the order of 1500 mm and exceed the rainfall rates from November to May. The south-west area experiences moderate to high duration of sunshine hours across and durations in excess of 8.5 hours outside the monsoon season are not uncommon. The driest month is December, with 6 mm of rain. Most precipitation falls in July, with an average of 351 mm. There is a difference of 345 mm of precipitation between the driest and wettest months.

The study area is vulnerable to cyclones during the pre-monsoon and post-monsoon season when storm surges can cause rapid increase of water level up to 4 m above the tide and seasonal levels. The south-west coast line is protected to some extent by the dampening effects of mangrove forest 'Sundarbans' although tidal surges can proceed up to the major rivers.

The climate in general is favorable for agriculture across the area throughout the year. Temperature, precipitation, humidity and wind are the few climatic parameters are described in detailed below.

Temperature
May is the warmest month of the year. The temperature in May averages 29.7 °C. In January, the average temperature is 18.9 °C. It is the lowest average temperature of the whole year. The average temperatures vary during the year by 10.8 °C.

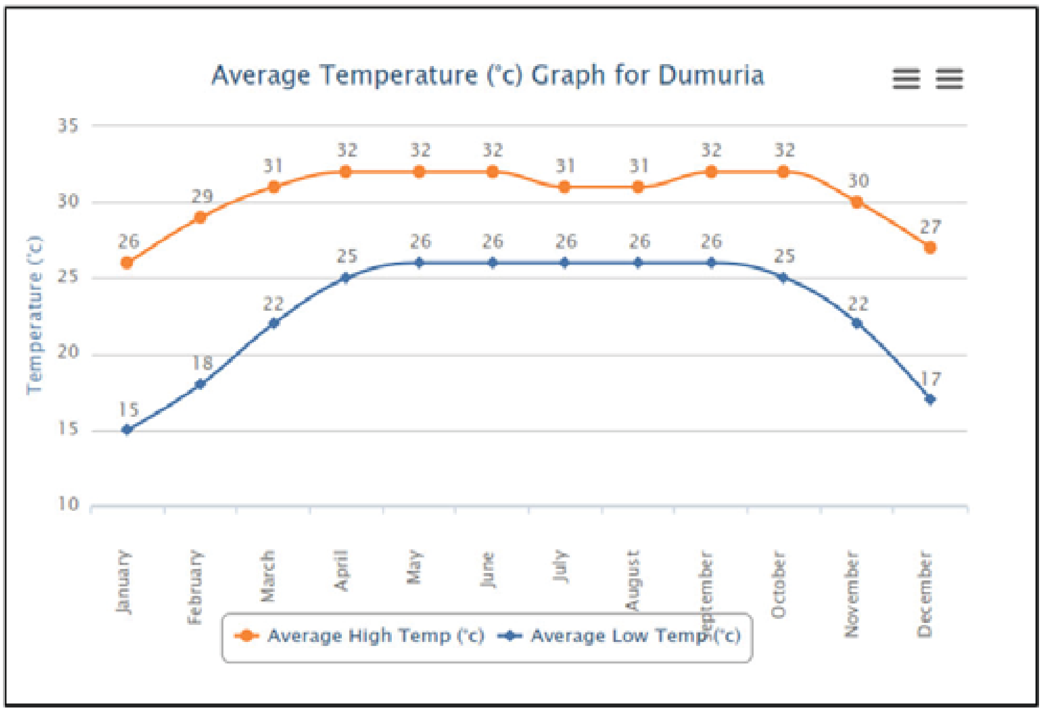

Figure 2-2: Temperature in the study area

Precipitation

Most of the precipitation occurs in July in the monsoon season. Highest average rainfall days are close to 15 in the month of July and total amount of precipitation in 15 days period is 295.5 mm.

Humidity

The area has high relative humidity, which varies from 70% in March to 89% in July. The annual average humidity in the region is 81.3%. Analysis of 1991-2000 data shows that the years of 1995 and 1996 had relatively low values of humidity.

2.3 Hydrology

Surface water resources of the study area originate from two separate but largely interlinked sources: surface water flows from Trans-boundary rivers, such as the Ganges/Padma and surface water originating from rainfall over the regions. Peak discharges occur in the Ganges in August and September. Boundary rivers the Ganges, the Padma and the Lower Meghna feed a number of regional rivers and channels. These rivers influence the water resources of the area directly through occasional over bank spill during flood and from regulated supply. The annual average flow of the Ganges in the pre-Farakka period was 11,690 m^3/sec and during post-Farakka period (1975-96) flow declined to 9,500 m^3/sec. After Ganges water as shearing treaty with India in 1996, mean flow for March increased to 1183 m^3/s from 526 m^3/sec as was during pre-Treaty period (Ref. SWAIWRMP, 2004). The flows in the major distributaries of the Ganges, the Gorai-Madhumati River area dependent on the Ganges discharge, morphological conditions of the Gorai itself and off take. The annual flow volume of the Gorai during the post-Farakka period has shown a decreasing trend. The only perennial stream that supplies fresh water into the Southwest area is the Arial Khan. It discharges water into the Madhumati-Nabaganga system through the Madaripur beel route with an average dry season fresh water flowof about 20 m^3/s. A further contribution from the Arial Khan enters the Swarupkati and Baleswar estuary system.

Surface water generated from local rainfall represents an important contribution to the water resources of the area since significant amount of rain water are held in storage in a large numbers of natural depression (in beel/haors etc).

The major tidal rivers are interlinked by numerous smaller channels and are sustained by tidal spill and surface water flows. The Pussur-Sibsa system receives a major part of its fresh water discharge from the Gorai-Madhumati during monsoon season. But condition of Pussur is deteriorating slowly due to siltation. The decreasing trend of dry season surface water availability causes significant morphological changes in the peripheral rivers systems of some coastal polders in the southwest region.

2.4 Surface Water Salinity

The salinity conditions in the tidal channels are highly dependent on the salinity at the coast and volumes of fresh water discharges from upstream. Semidiurnal variation of salinity occurs in the tidal basin and salinity varies over a number of different time scales. The rivers of this region start to be affected by coastal saline water from the month of November.

The salinity increases steadily from December through February, reaching maximum in late March and early April following minimum flow in the Ganges .

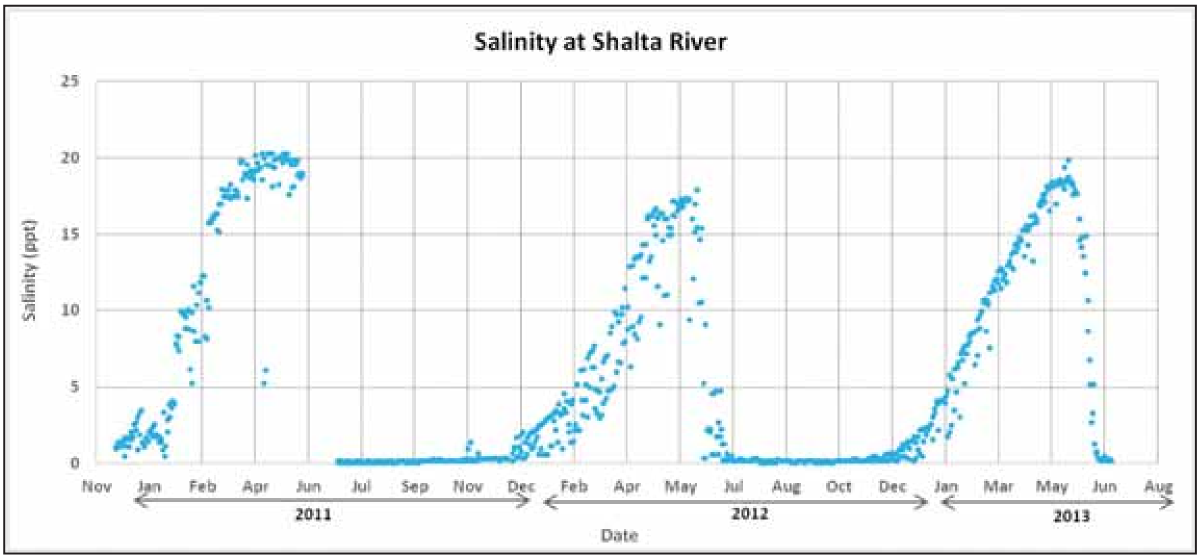

Figure 2-3: Temporal distribution of salinity level in the Shalta river

Figure 2-3 shows the salinity variation in different period of the year in the Shalta River. Salinity starts from mid December and maximum salinity reaches up to 20 ppt in April 2011. Equation 1.1 is used to express the variation of settling velocity with salinity.

$$w_{saline} = w_s \left(1 - C_1 e^{C_2}\right) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1.1)$$

Where, C_1 and C_2 are calibration parameters.
w_{saline} = Settling velocity for saline water (>5 ppt)
w_s = settling velocity for non saline water

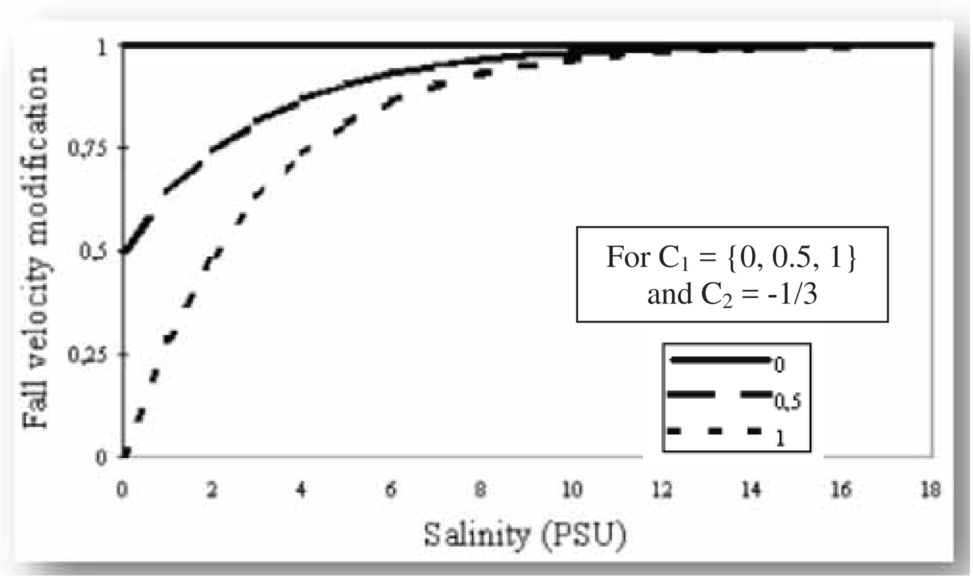

Figure 2-4: Settling velocity and salinity dependency

3 DATA AND ANALYSIS OF DATA

3.1 General

A comprehensive attempt has been made for the collection of field data of tide, water flow, river cross-section, sediment sample and satellite image and secondary data from different sources at key locations along the peripheral rivers of the polders to understand the tidal and sediment characteristics of these rivers. Hydrodynamic modelling has been carried out for determination of erosion prone stretch of the river bank and assessing effectiveness of erosion mitigation measures. The field survey campaign was carried out at two phases: dry (April ~ May, 2015) and Monsoon (July ~ August, 2015) to collect the data on river cross-section, water level, water flow, velocity, river bed materials and suspended sediment concentration. All these data have been checked and validated using standard data quality control procedures before using in the study.

3.2 Primary Data

Primary data on bathymetry, land, water level, sediment concentration, bed samples were collected through direct field observation during both monsoon and dry period. The summary of collected data is shown in Table 3-1 and in Figure 3-1

Table 3-1: Description of data collected during the survey Programme in 2015

Sl. No.	Item	Location & Nos.	Measurement Specification	Completed Survey	Method
1	Bathymetry Survey	Lower Bhadra River (part)	@100m inerval	May, 2015	DGPS Digital Eco-sounder, HydroPro Software
2		Lower Shalta, Lower Bhadra(part), Gangreil & Haborkhali River	@250m interval		
3	Water Level	Raipur (Bhadra River)	1 hour interval	21/04/2015 – 15/05/2015	Tidal Gauge
		Kollan Sree (Bhadra River)	30 min interval	09/09/2015 – 28/09/2015	
4	Discharge	Baroaria Bazar (Bhadra & Haborkhali River), 4 nos.	1 hour interval (from 6:00 am – 6:00 pm)	28/07/2015 – 30/07/2015 (both spring &neap tide)	Acoustic Doppler Current Profiler (ADCP)
5	Suspended Sediment Sampling	Same as discharge measurement, 141 nos.	do	do	
6	Bed Material Sampling	10 nos.		Dry period	Grab Sampler

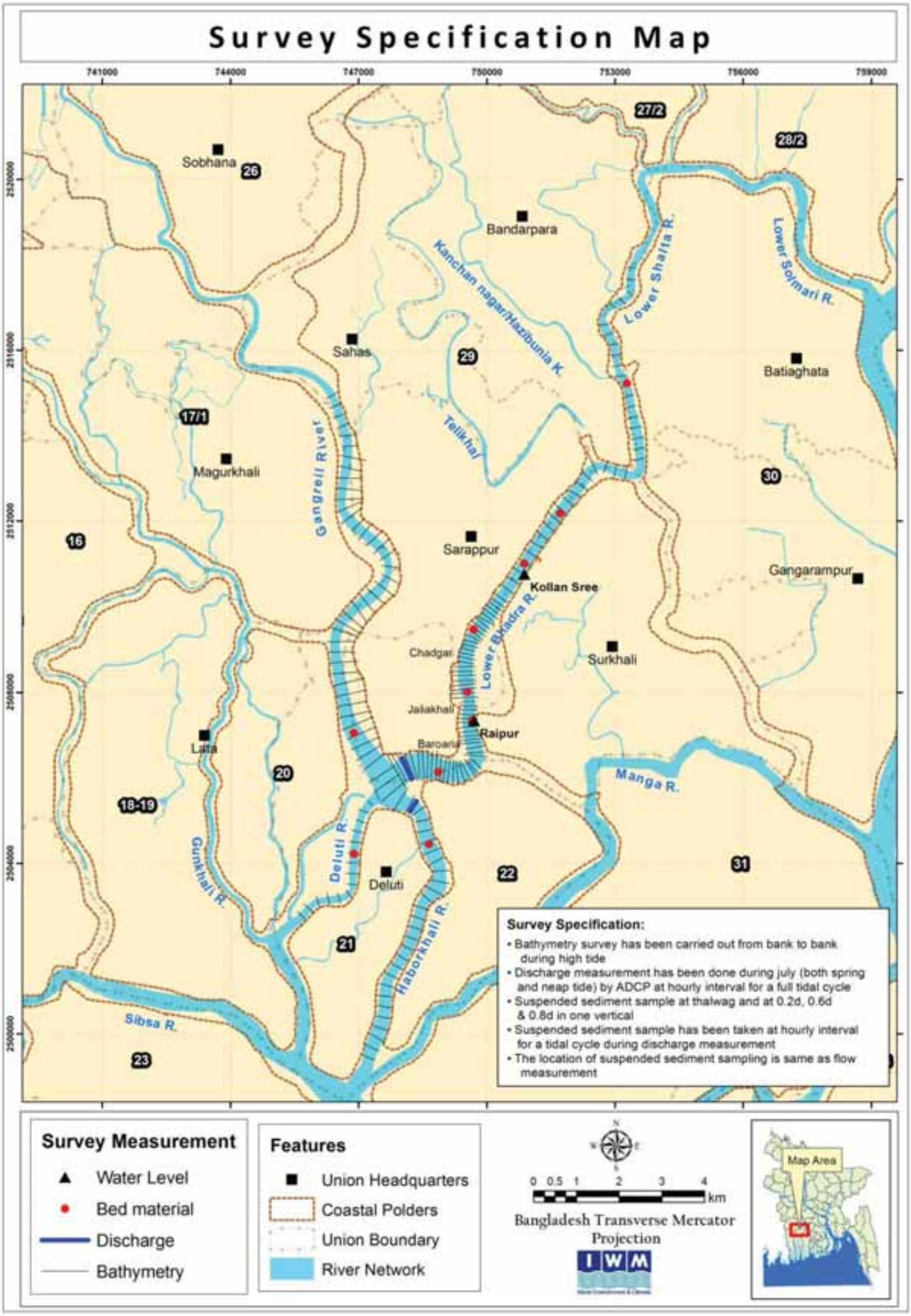

Figure 3-1: Bathymetry survey transect and water level, flow, bed material collection locations

3.2.1 Bed Topography Survey of River

The bed topography survey of the channel bed for this project was done to cover the area which is relevant for the study. The reason of the surveying was to collect the present data for developing the hydrodynamic model. To get the bed topography, the river was surveyed in most places keeping 100 m to 250 m interval between two consecutive surveys transect. The project work is aimed to mitigate the erosion problem along the embankment of polder 29. River bed topography survey has been carried out at 100 m interval in places along the right bank of lower Bhadra river, where the erosion tendency was severe and hence closer observation is useful for model development.

The total length of the bed topography survey, if the length of each transect is added together, is around 85 Km. The surveyed location of transects are shown in Figure 3-1.

3.2.2 Water Level Measurement

Water level data is important to know the variation of water depth over the year, tidal characteristics and also to calibrate the Hydrodynamic model. Here water level observations were made at two locations near Raipur at one hour interval from 21/04/2015-15/05/2015(6AM to 6 PM) and near Kollansree at half hour interval from 09/09/2015-30/07/2015 (6AM to 12 AM) in Lower Bhadra river .

The water level measurement stations are at the left bank of the Lower Bhadra River which is at the erosion prone area.

Locations of water level measurement station are shown in Figure 3-1

Water level data is measured in meter in reference to Public Works Datum (PWD). A sample plot of water level data at the tide gauge located near Chadgar is shown in Figure 3-2

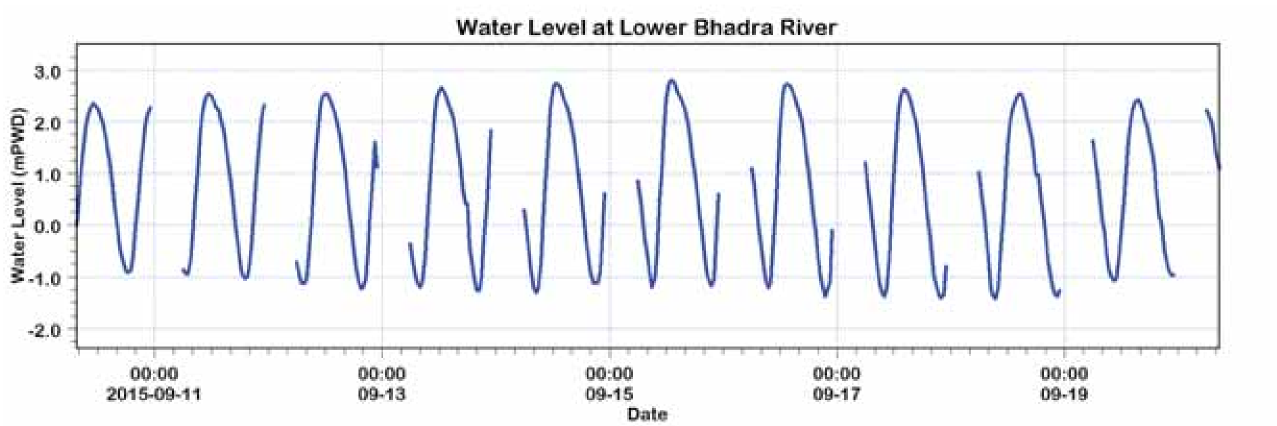

Figure 3-2: Variation of tidal water level with surveyed data in Lower Bhadra river

It is observed that the tidal range is 4.67 m at lower Bhadra River. Again, the highest water level is 2.94mPWD and the minimum is -1.73 m PWD during the measuring period. Water Level is also collected from Secondary Sources.

3.2.3 Flow Measurement

The tidal discharge was measured with the help of Acoustic Doppler Current Profiler (ADCP).The discharge measurement was carried out for 13 hours with one hour interval at Lower Bhadra River and at Haborkhali river near Baroaria Bazar (Figure 3-1). At both locations discharge measurements were carried out both in spring and neap tide. The purpose of these measurements was to know about the water flow during flood and ebb tides, tidal prism and to calibrate the model. The locations of discharge measurements are shown in Figure 3-1.Sample of the measured tidal discharge data is shown in Figure 3-3 and Figure 3-4.

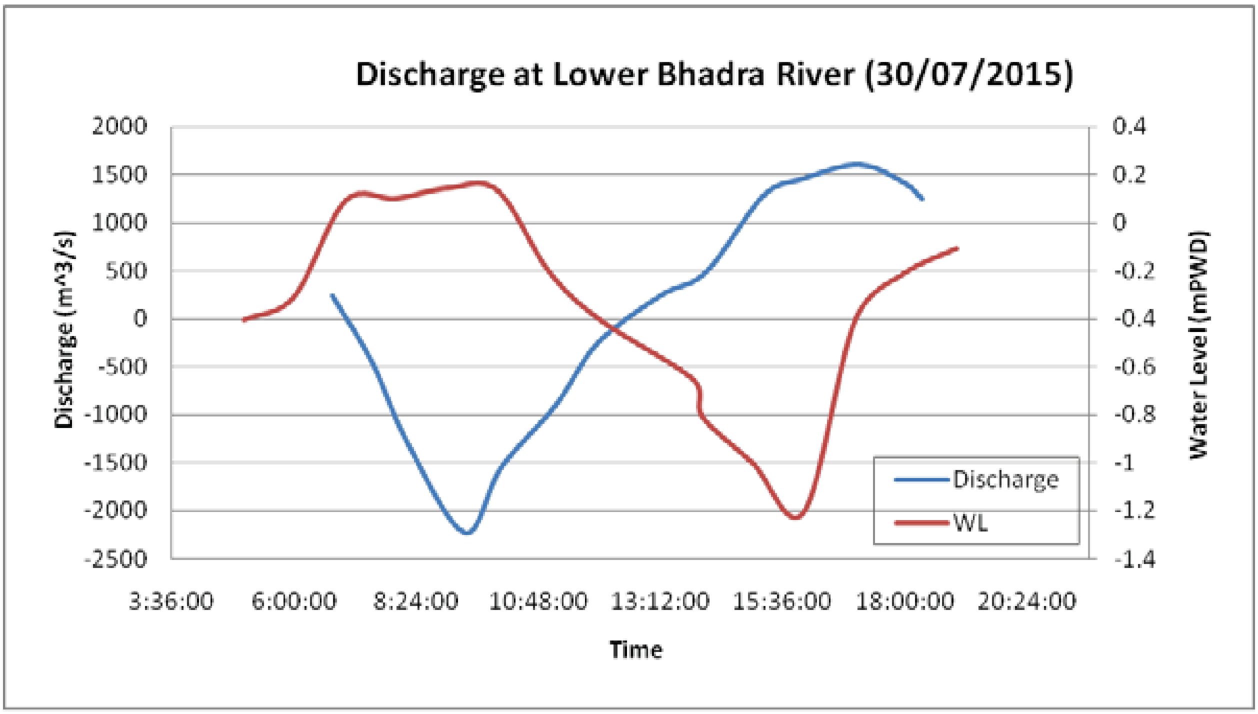

Figure 3-3: Measured discharge at Haborkhali River on 30th July, 2015 (spring tide)

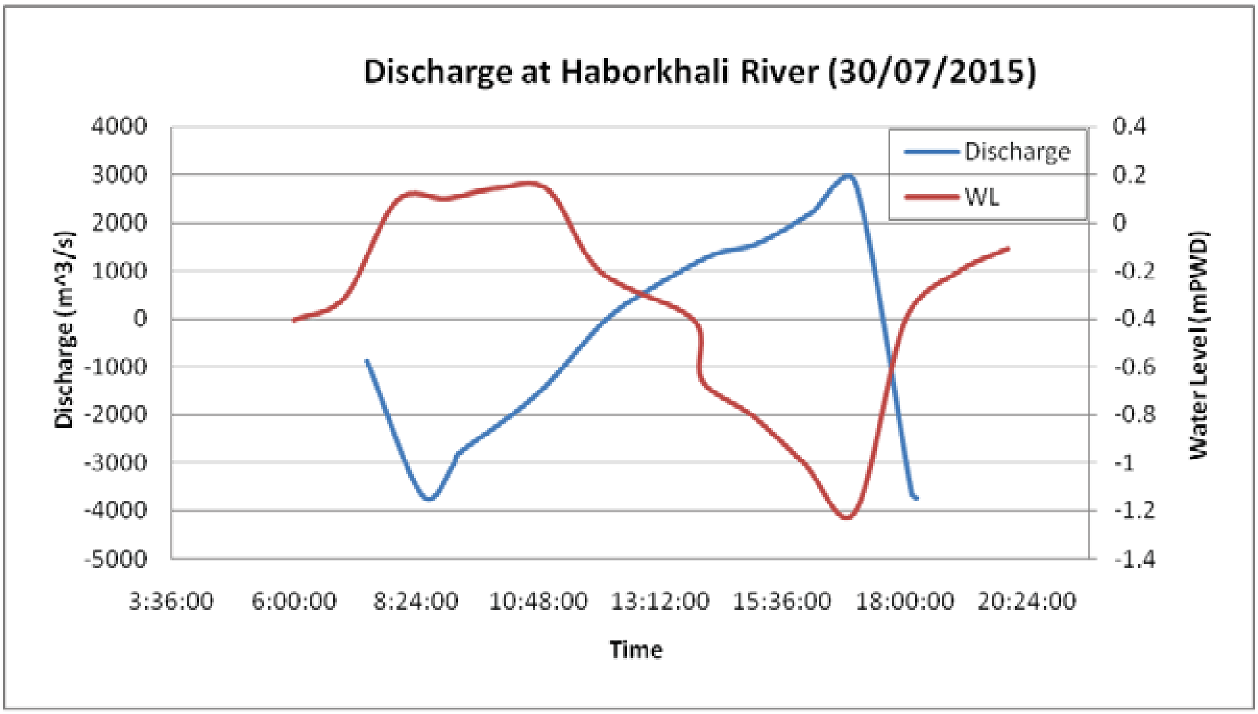

Figure 3-4: Measured discharge at Haborkhali River on 30thJuly, 2015 (spring tide)

It is observed that maximum discharge during the measurement is at least 3,724 m^3/s at Haborkhali river during spring at flood (high) tide. The maximum discharge at two locations during flood and ebb tides is presented in the Table 3-2.

Table 3-2: Maximum measured discharges during spring and neap tide

Sl. No.	Location	Measurement Period	Type of tide	Measured Max Flow during Ebb tide (m^3/s)	Measured Max Flow during flood tide (m^3/s)
1	Lower Bhadra River	28/07/2015 (half hourly)	neap	1378	1286
		30/07/2015 (half hourly)	spring	2228	1607
2	Haborkhali River	28/07/2015 (half hourly)	neap	2471	3144
		30/07/2015 (half hourly)	spring	3724	2836

3.2.4 Sediment Measurement

Bed materials were collected and analyzed at several locations of the Lower Bhadra, Gangreil, Haborkhali and Deluti River. A total of 10 bed material samples were collected at different locations of the river bed. The locations from where bed samples were collected are shown in Figure 3-1. Analysis was done to get an idea and information on spatial distribution of the bed material. The median values of the grain size (D_{50}) were calculated. Table 3-3shows the calculated median grain size at different locations. In Table 3-3the locations are given in BTM coordinates. The data shows that, the bed material of Lower Bhadra River is sandy. D_{50} varies from 92 to 187 micron in Lower Bhadra.

Table 3-3: River bed material sample collection location and median grain size

Sl._No.	River Name	BTM Coordinates		D_{50} (mm)
		Easting (m)	Northing (m)	
1	Lower Shalta	445451.197	512920.994	0.030
2	Lower Bhadra	443816.462	509924.737	0.125
3		442966.634	508723.577	0.092
4		441737.132	507231.229	0.171
5		441537.569	505812.015	0.160
6		440818.937	503879.545	0.108
7		441600.504	505117.114	0.187
8	Gangreil	438902.220	504884.710	0.157
9	Deluti	438818.433	501968.892	0.180
10	Haborkhali	440595.260	502253.913	0.141

Suspended Sediment

In order to know the sediment transport pattern, sediment concentration measurement is needed. Suspended sediment concentration was measured during each discharge measurement at spring and neap tide. The suspended sediment collection points are located along the two discharge measuring transects. Samples were collected from one vertical from each of transect. The samples have been collected every hour for the full tidal cycle of 13 hours. At a particular vertical point three samples were collected each time at depths 0.2d, 0.6d and 0.8d depth measured from water surface, where d is the depth of a vertical.

A sample plot of sediment concentration measured at Lower Bhadra River is shown in Figure 3-5 and Figure 3-6

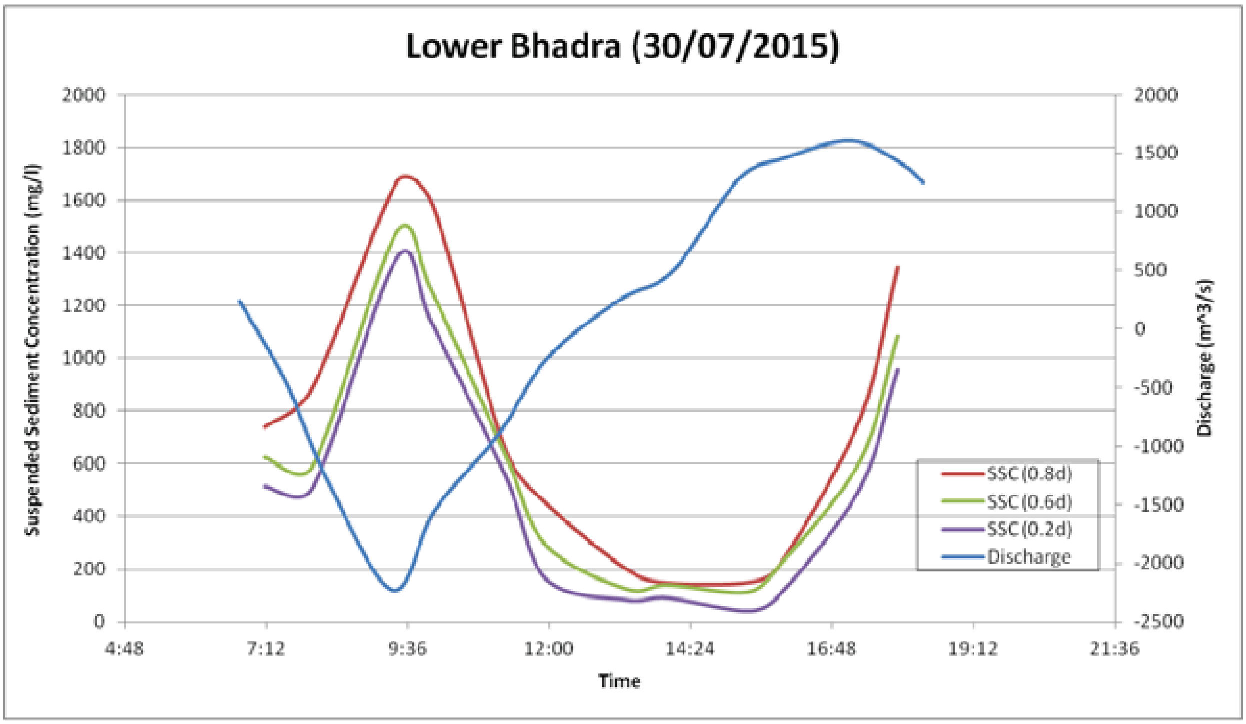

Figure 3-5: Sediment concentration at Bhadra River with the measured discharge data on 30th July, 2015

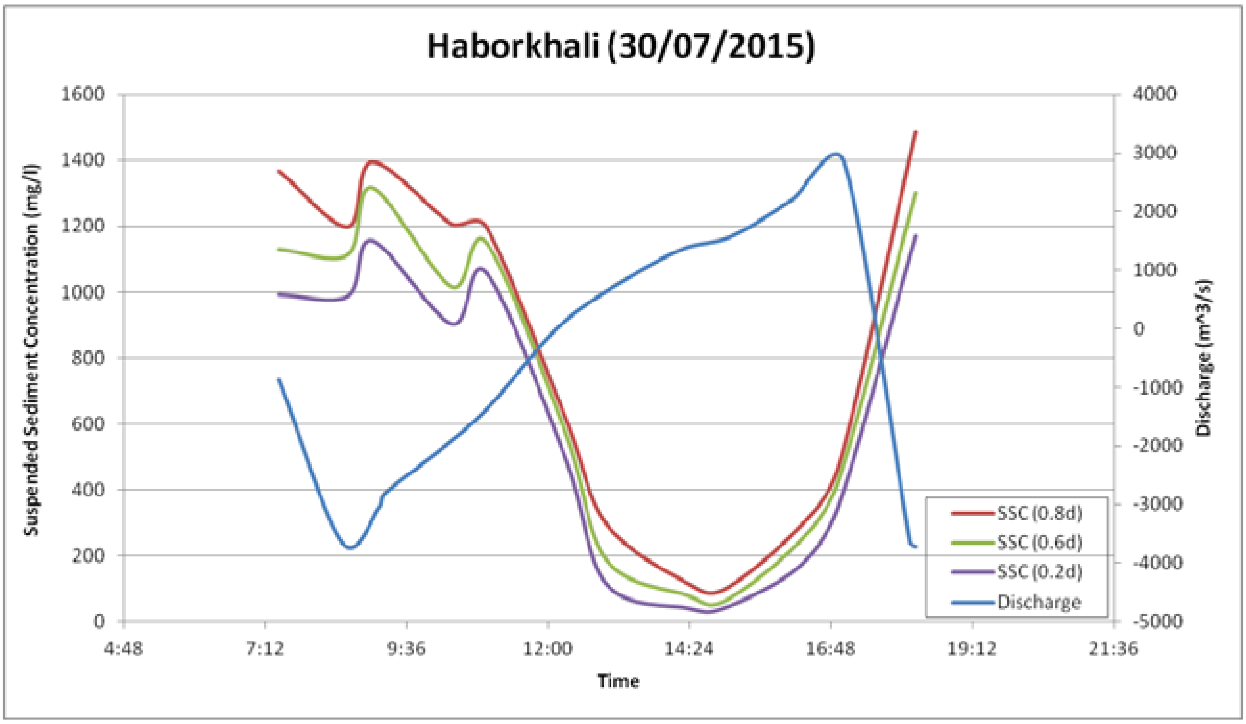

Figure 3-6: Sediment concentration at Haborkhali River with the measured discharge data on 30th July, 2015

Figure 3-5 & Figure 3-6 shows that the maximum suspended sediment concentration is 1672 mg/l at Bhadra River and 1486 mg/l at Haborkhali River during Flood period on 30th July, 2015 at 0.8d depth. It also shows that when the discharge is maximum, the sediment concentration is also maximum. The depth average maximum, minimum and average sediment concentrations are given in Table 3-4 & Table 3-5.

Table 3-4: Depth average maximum, minimum and mean concentration of suspended sediment measured at different locations during spring tide

Name of the Location	Date of measurements	Spring Tide		
		Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)
Lower Bhadra (Baroaria Bazar)	30/07/2015	1491	82	590
Haborkhali (Baroaria Bazar)	30/07/2015	1290	61	695

Table 3-5: Depth average maximum, minimum and mean concentration of suspended sediment measured at different locations during neap tide

Name of the Location	Date of measurements	Neap Tide		
		Maximum (mg/l)	Minimum (mg/l)	Mean (mg/l)
Lower Bhadra (Baroaria Bazar)	28/07/2015	471	49	221
Haborkhali (Baroaria Bazar)	28/07/2015	486	73	229

Suspended sediment concentration is high during spring tide. Measurement indicates suspended sediment concentration is about 3 times higher during spring tide than that of neap tide.

To measure the mean value of the sediment, the depth average sediment concentration for each vertical for each time was calculated first. The following equation was used in computing dept-averaged concentration.

$$\begin{aligned} &\mathit{Depth\ average\ sediment\ concentration} \\ &\quad = \frac{5}{8}(\mathit{sediment\ concentration\ at}\ 0.2d) \\ &\quad + \frac{3}{8}(\mathit{sediment\ concentration\ at}\ 0.8d) \end{aligned}$$

At each vertical, 13 depth averaged sediment concentration was calculated for 13 particular times for covering the whole tidal cycle. Out of those 13 values, maximum, minimum and the arithmetic mean values are shown in the table above.

3.3 Secondary Data

Data on water level, discharge, and bathymetry were collected from secondary sources. These water level and discharge data have been used for calibration of hydrodynamic model.

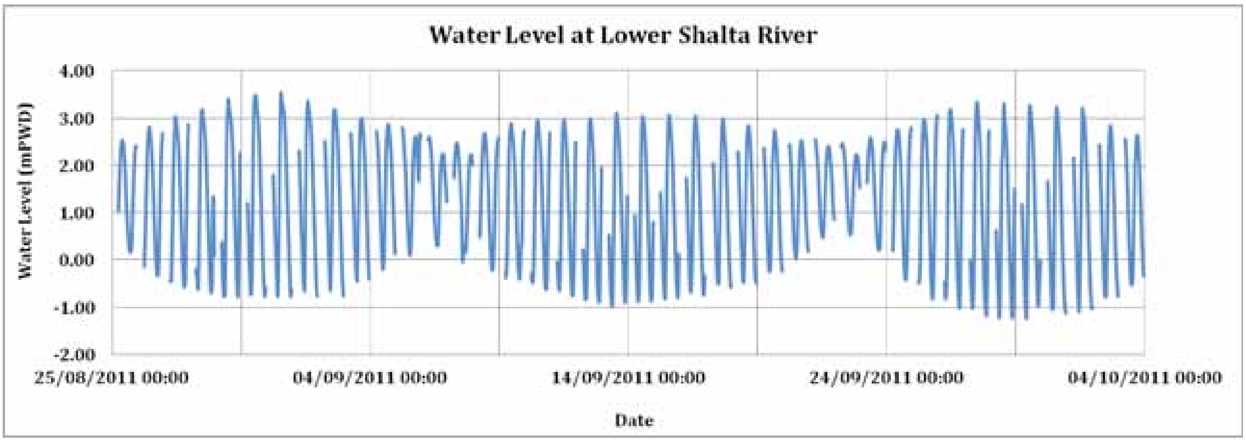

Figure 3-7: Water Level at Lower Shalta river is collected from secondary sources.

3.3.1 Satellite Image

In order to analysis of River bank line shifting characteristics, satellite images of the study area were purchased from Bangladesh Space Research and Remote Sensing Organization (SPARRSO) and CEGIS. The inventory of the purchased images is given below.

Table 3-6: List of Satellite Images

SI No.	Year	Type of Image	Resolution
1	2011	Rapid Eye	5 m
2	2015	Rapid Eye	5 m

Also Google Earth images were used in the analysis.

4 MODEL DEVELOPMENT AND CALIBRATION

4.1 Governing Equations

Shallow water equations

The MIKE 21 Flow Model is based on the solution of the two-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure.The local continuity equation integrated over depth (2D) can be written as:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS$$

Where, h is the water depth
u and v are water particle velocities in x and y direction respectively,
S is the magnitude of the discharge due to point sources.

The overbar indicates a depth average value. For example, $\bar{u}$and $\bar{v}$are the depth-averaged velocities defined by

$$h\bar{u}=\int_{-d}^{\eta}udz, h\bar{v}=\int_{-d}^{\eta}vdz$$

The two depth averaged, horizontal momentum equations for x- and y-components are, respectively (Holthuijsen, 2007):

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\overline{vu}}{\partial y}=fh\bar{v}-gh\frac{\partial\eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial\rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y}\right)$$
$$+\frac{\partial}{\partial x}(hT_{xx})+\frac{\partial}{\partial y}(hT_{xy})+hu_sS \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4.1)$$

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{v}^2}{\partial y}+\frac{\partial h\overline{vu}}{\partial x}=-fh\bar{u}-gh\frac{\partial\eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial\rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)$$
$$+\frac{\partial}{\partial x}(hT_{xy})+\frac{\partial}{\partial y}(hT_{yy})+hv_sS \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4.2)$$

here t is the time;
x and y are the Cartesian co-ordinates;
η is the surface elevation;
d is the still water depth;
$h=\eta+d$ is the total water depth;
u and v are velocity components in x and y direction;
f is the Coriolis parameter;
g is gravitational acceleration;
ρ is the density of water
s_{xx}, s_{xy}, s_{yx} and s_{yy} are components of the radiation stress tensor
S is the magnitude of the discharge due to point sources
(u_s, v_s) is the velocity by which the water is discharged into the ambient water
p_a is the atmospheric pressure
$\rho_0$is the reference density of water;
τ_{sx}, $\tau_{sy}$are the x and y components of surface wind
$\tau_{bx}$and $\tau_{by}$are the components of bottom stress;

The lateral stresses T_{ij} include viscous friction, turbulent friction and differential advection. They are estimated using an eddy viscosity formulation based on depth averaged velocity gradients

$$T_{xx} = 2A\frac{\partial \bar{u}}{\partial x}, T_{xy} = A\left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x}\right), T_{yy} = 2A\frac{\partial \bar{v}}{\partial y}$$

Where A is the horizontal eddy viscosity.

The right-hand side of Equation (4.1) and (4.2) constitute the input and boundary conditions provided to any model to calculate the current components and water particle velocities. The solution of these equations is dependent on the scheme applied by the model and different assumptions may result in different outcome. The resulting values of current and water particle velocities are responsible for sediment transport occurring in the tidal rivers.

Turbulence modelling is usually included in the momentum equations in the terms containing laminar stresses and Reynolds stresses. It can be either used as a constant in the horizontal stress terms or by using the Smagorinsky's formulation (1963) to express sub-grid scale transports by using an effective eddy viscosity related to characteristic length scale (Lily, 1989).

4.2 Hydrodynamic Model

The present study outputs are largely based on the simulation results of two-dimensional Model. The modelling system used for the development of Model is the MIKE21 FM, which is based on an unstructured flexible mesh consisting of linear triangular and rectangular elements. The mesh enables to increase the resolution of grid around Islands, along bank-line and other area of interest.

In order to investigate the hydraulic characteristics such as water level fluctuations, velocity distribution, variation of river flow with tide, net flow during dry and monsoon seasons, a hydrodynamic model of the rivers in the study area has been developed. The model includes the peripheral rivers of polder 29. The tidal rivers Bhadra, Gangreil, Haborkhali and Deluti are included in the model set up. The coverage of the numerical model is shown in Figure 4-1 and computational grid or mesh developed to represent the two-dimensional vectors of flow is also shown in Figure 4-1. The grid or mesh size decreases (or the resolution increases) at the erosion prone area near the right bank of Bhadra river. The inter-tidal areas are flooded and dried during a tidal cycle, both in nature and in the model also.

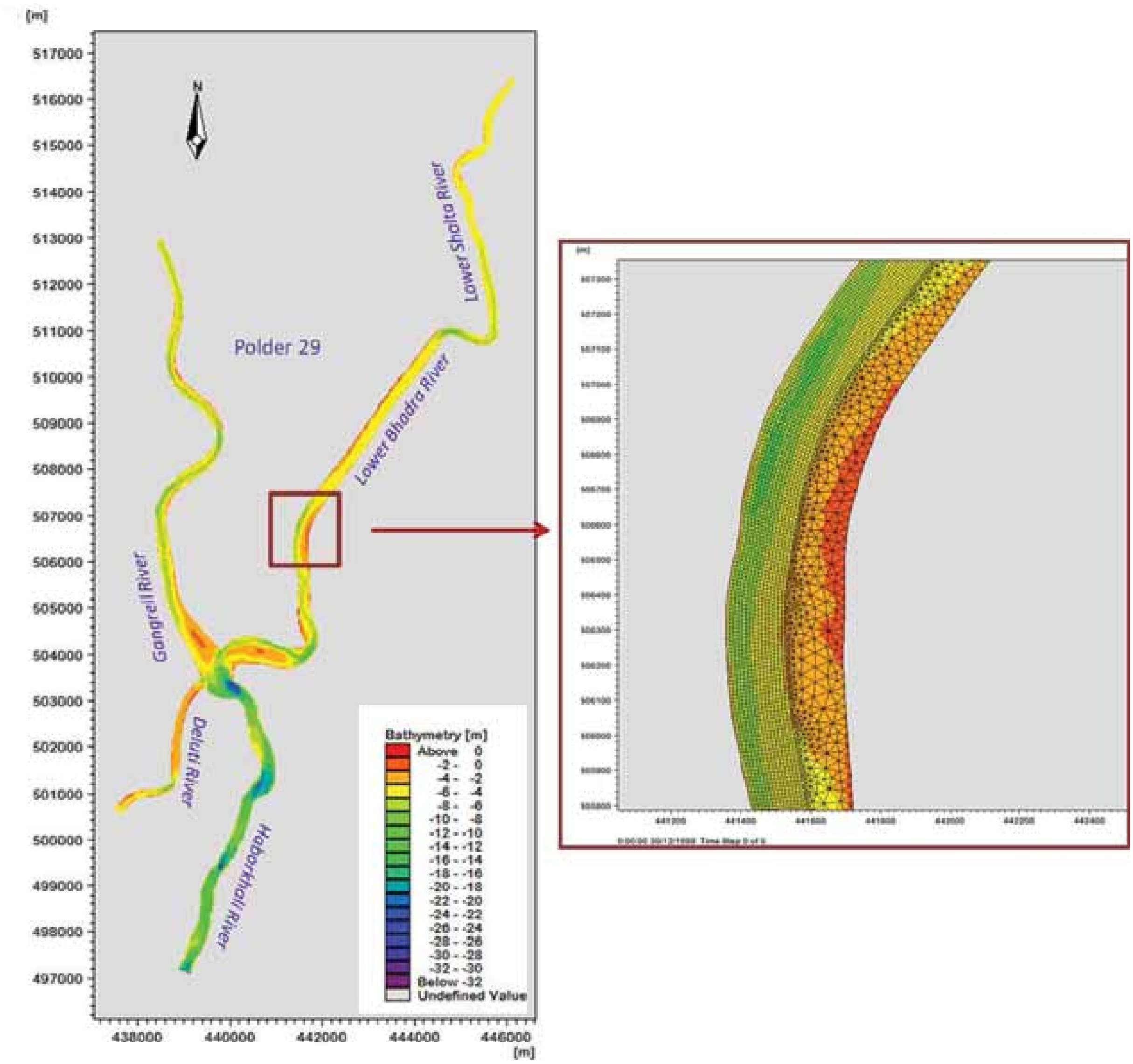

Figure 4-1: Computational grid or mesh to represent the two-dimensional vectors of the river flow

4.3 Calibration and Validation

The hydrodynamic model has been calibrated against measured water levels and discharges for the monsoon period at different locations comparing the model results with field measurement to make the model performance to a satisfactory level. The model results have also been examined with other set of data of different year and location compared to the data used in the calibration to validate the model. Figure 4-2shows some of the calibration results. The comparison shows reasonable and satisfactory agreement of model results with the measured water flow. The calibrated model has also been used to establish flow characteristics of the rivers in the study area.

4.3.1 Calibration of the Model

Water Level Calibration

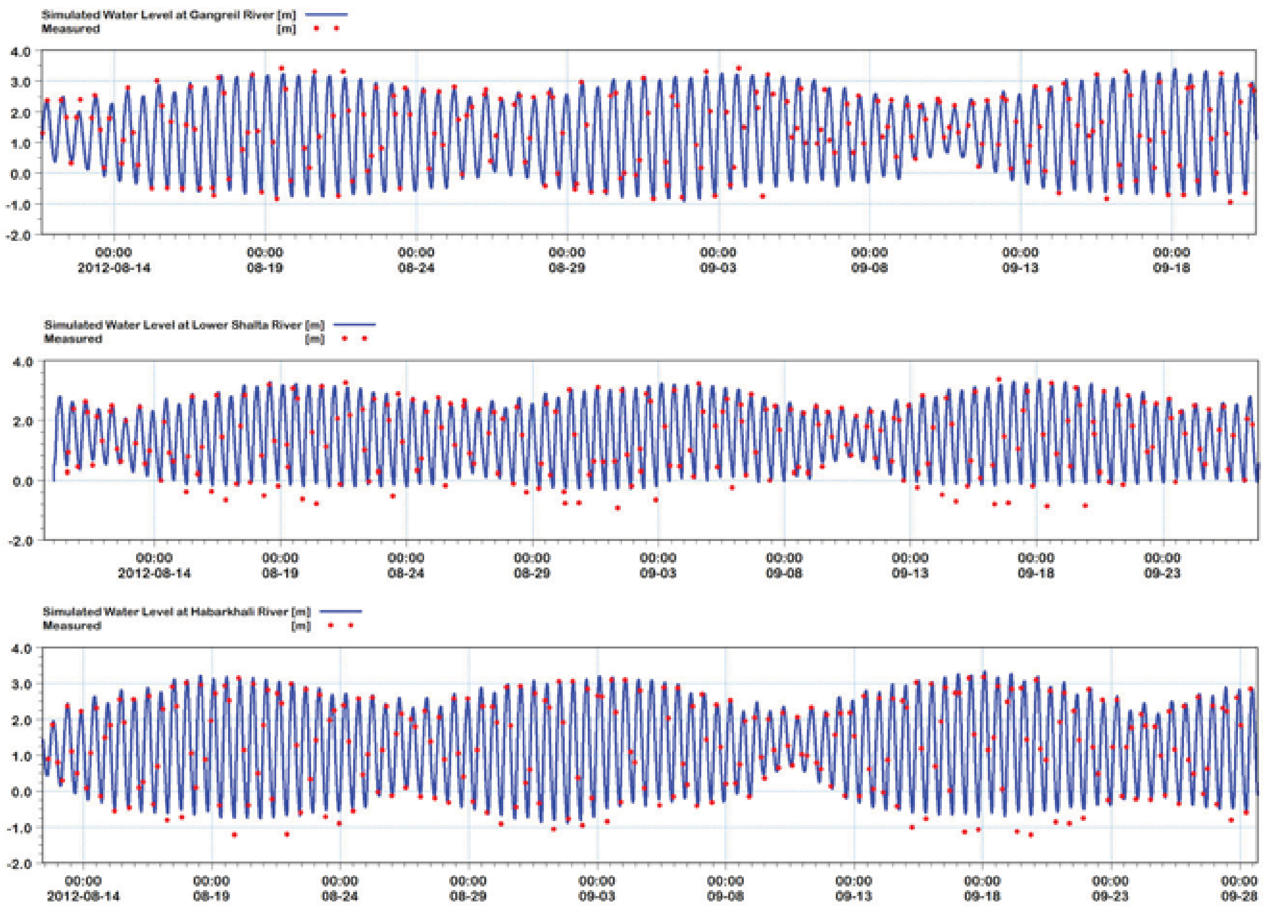

Figure 4-2: Calibration of water level at Gangreil, Shalta and Haborkhali River

Discharge Calibration

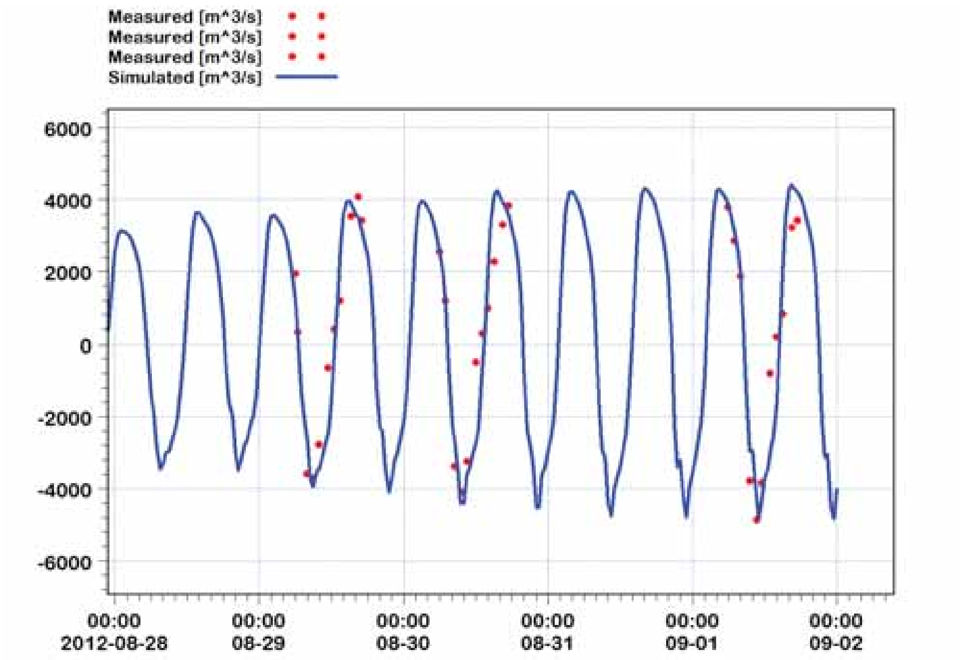

Figure 4-3: Discharge calibration plot at Haborkhali River monsoon 2012

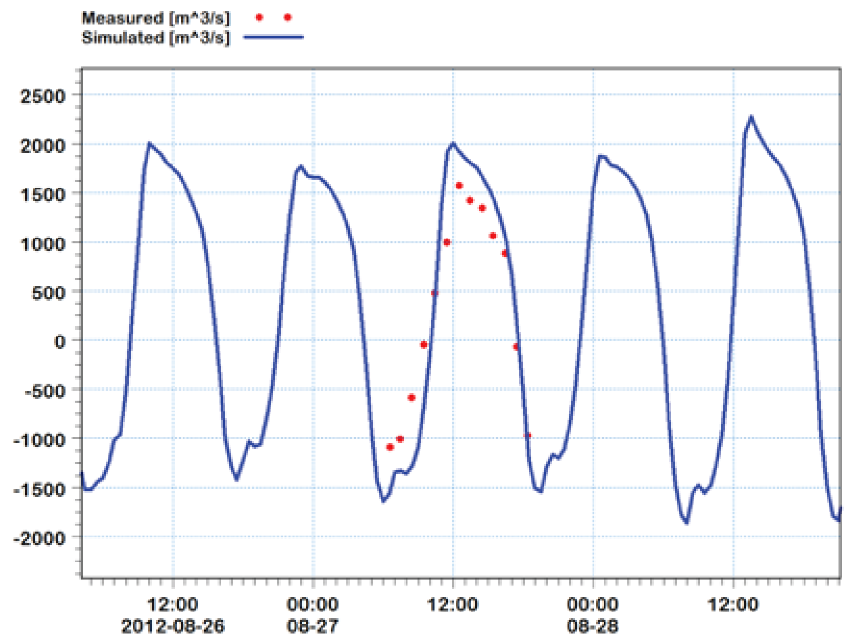

Figure 4-4: Discharge calibration plot at Lower Bhadra River monsoon 2012 in neap tide

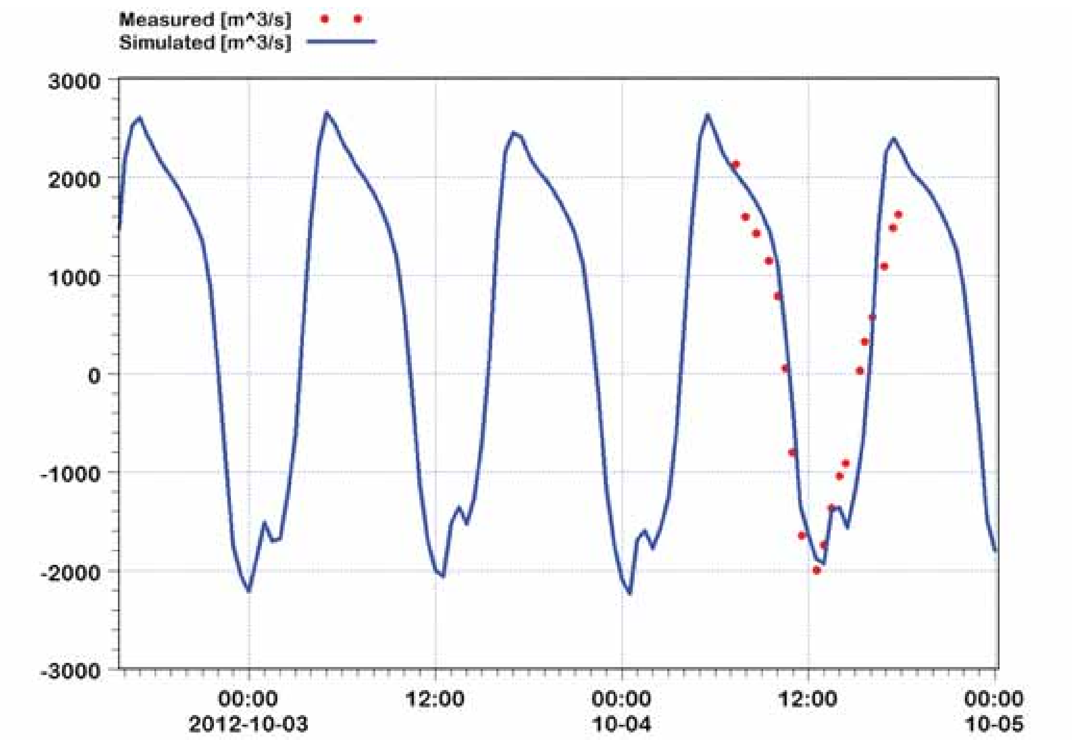

Figure 4-5: Discharge calibration plot at Lower Bhadra River monsoon 2012 in spring tide

4.3.2 Validation of the Model

Water level Validation

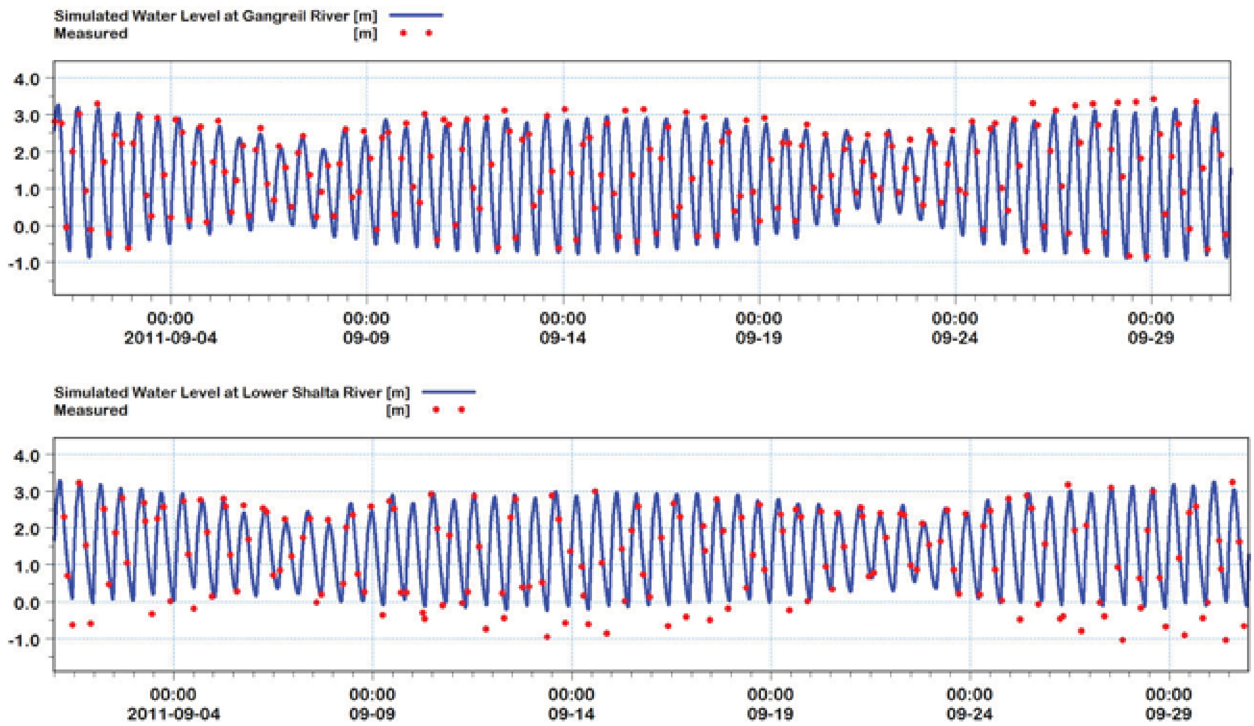

Figure 4-6: Validation of water level at Gangreil and Shalta River

Discharge Validation

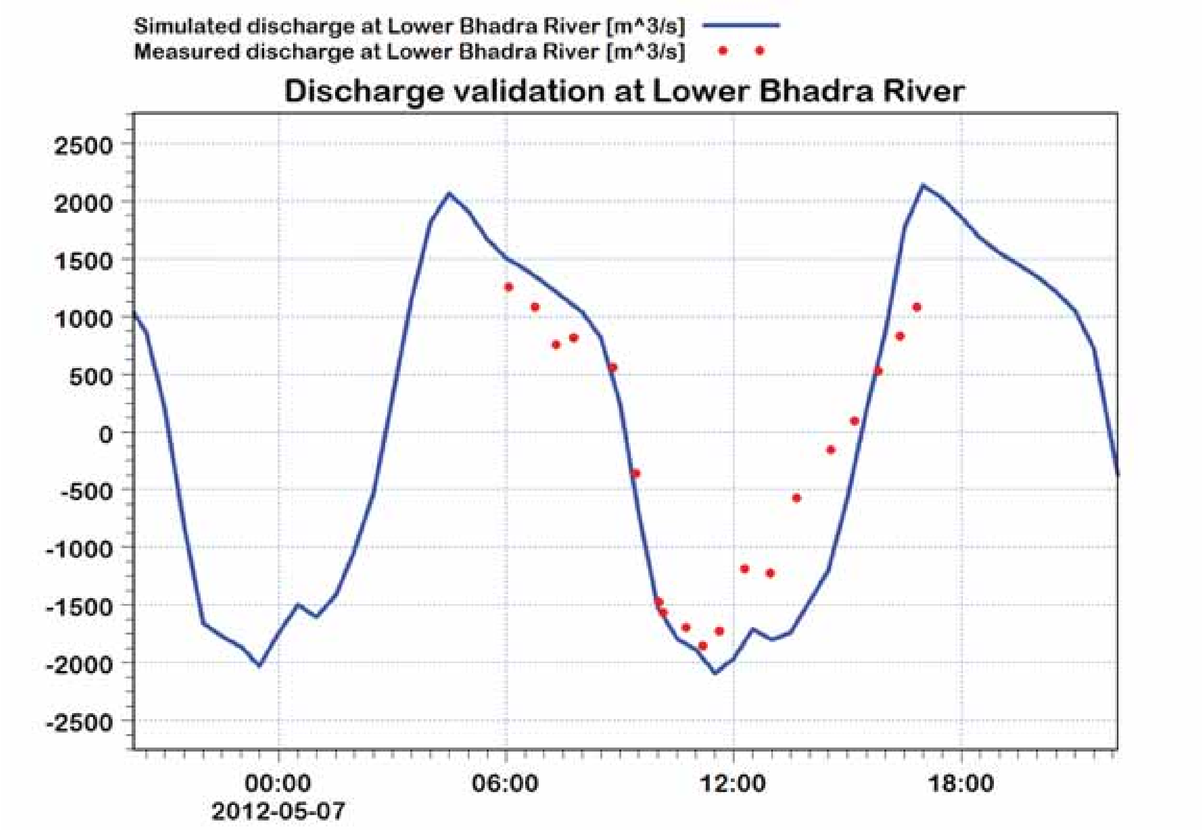

Figure 4-7: Discharge validation plot at Lower Bhadra River dry 2012 in spring tide

5 ESTABLISHMENTOF BASELINE CONDITION AND IDENTIFICATION OF EROSION VULNERABLE AREA

5.1 Hydraulic Condition

The hydrological processes involved in the Lower Bhadra River are tide, current speed, discharge, salinity and sediment transport. In this study, 2012 has been considered as baseline period.

5.1.1 Flow, Tide, Tidal Prism, Net Flow Distribution and Current Field

Flow

The Lower Bhadra and Gangreil River conveys the drainage water from polder 29 and polder 30 to Sibsa River through Haborkhali and Deluti river during low-tide. Flow varies in dry and monsoon period and also in spring and neap tide. From the measurement, maximum discharge during spring tide monsoon period is 2228m^3/s and in neap period it is 1378m^3/s in Lower Bhadra river.

Tide

Tidal waves approaching the coastal areas of Bangladesh are affected at least by four factors causing amplification and deformation of the wave: 1) Coriolis acceleration 2) the width of the transitional continental shelf 3) the coastal geometry and 4) the frictional effects due to fresh water flow and bottom topography. Tide arrives from the deep sea and approaches at Hiron point and Cox's Bazar at about the same time. The water level variation is dominated by a semi diurnal tide having the main constituents M2 and S2 with considerable variation from neap to spring tide. In the entire coastal area the variation of amplitude from spring to neap is from 0.6 to 1.4 times the average amplitude. Polder 29 is located 111 km away from the sea but tidal influence is huge here. Tidal range in spring tide is about 4.67m and in neap tide it is about 2m.

Tidal Prism

Tidal Prism is an indicator for stability of a tidal channel. The total volume of flood and ebb tide in one tidal cycle is known as tidal prism. O'Brien (1931, 1969) examined field data from tidal inlets through sandy barriers in the West Coast of the United States and determined a relationship between the minimum cross-sectional flow area of the entrance channel and the observed tidal prism and established an equation in the form (Ref. /1/):

$$A_c = CP^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, A_c is the minimum inlet cross-sectional area in the equilibrium condition, C is an empirically determined co-efficient, P is the tidal prism and n is an exponent.

For southwest region of Bangladesh the relationship is found to be:

$$A_c = 43.42P^{0.9985} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where,
P = mean tidal prism (ebb + flood) in million m^3

A_c = cross-sectional area below mid tide level in m^2

Any significant change in tidal prism cause considerable morphological change in the channel i.e. if it is reduced then sedimentation will occur and if it is increased then scouring or erosion will take place. The tidal prism in Lower Bhadra river during monsoon is 67 million m^3 and in dry period it is about 50 million m^3.

Current Speed

Figure 5-1 and Figure 5-2 show the maximum depth average velocity field with contour in the Lower Bhadra River during dry and monsoon period. The maximum depth integrated velocity in dry period (Feb 9-Feb 26, 2012) varies from 1.75- 1.25 m/s along the Lower Bhadra river near Chadgar, Jaliakhali. Current speed is relatively lower near Baroaria. Near Baroaria current speed varies from 1.00 m/s to 0.50 m/s in dry period.

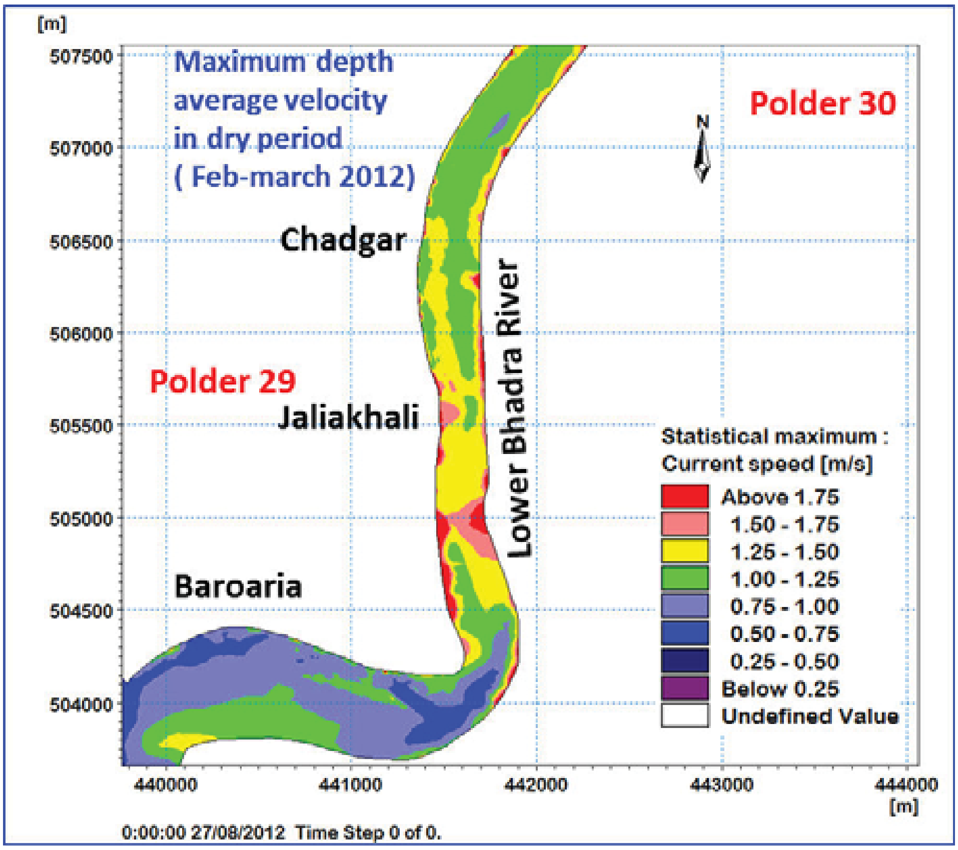

Figure 5-1: Depth average velocity in dry period (Feb 2012)

In monsoon, current speed is higher compare to dry season. Along the Lower Bhadra river maximum depth average velocity (August 26-Sept 12, 2012) near the bank varies from 2.50-1.75 m/s near Chadgar and Jaliakhali and near Baroaria it varies from 2m/s to 1.75 m/s.

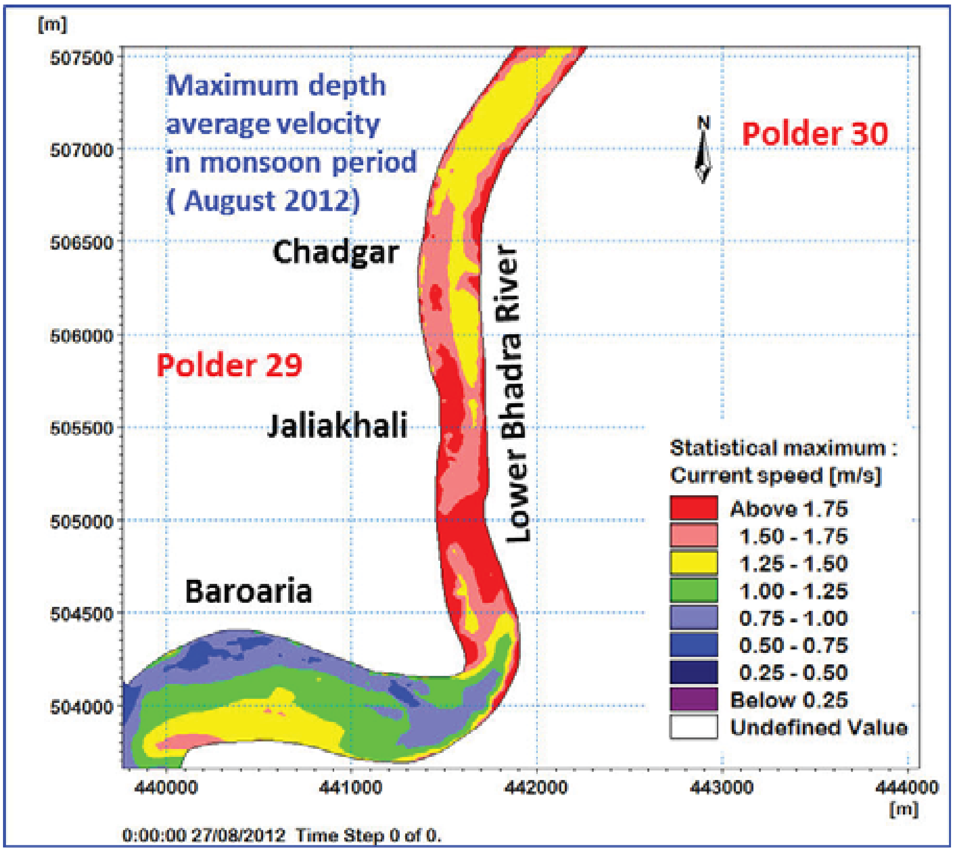

Figure 5-2: Depth average velocity in monsoon period (Aug-Sept 2012)

5.2 Accretion-Erosion Rate Over the Past Years

5.2.1 Cross-section Analysis

In the survey program mentioned in3.1, through bathymetric survey new cross sections of the river have been obtained. Some of the cross sections were compared among one another.

The Lower Bhadra river is almost straight with an average width of 330 m near Sarafpur Bazar. The width increases gradually to the confluence of four tidal river namely Bhadra, Gangreil, Haborkhali and Deluti river near Baroaria Bazar.

Figure 5-3 shows some selected cross sections plotted from the recent bathymetry survey data. These cross-section profiles are drawn from right bank to left bank for the entire length of Lower Bhadra River. Here, it is evident that the deepest water course is flowing along the right bank at Chadgar and at Baroaria Bazar. There is no or little setback distance between embankment and river bank. Also very steep slope prevails at these locations. This indicates that the right bank near Chadgar and Baroaria Bazar is under severe attack of bank erosion.

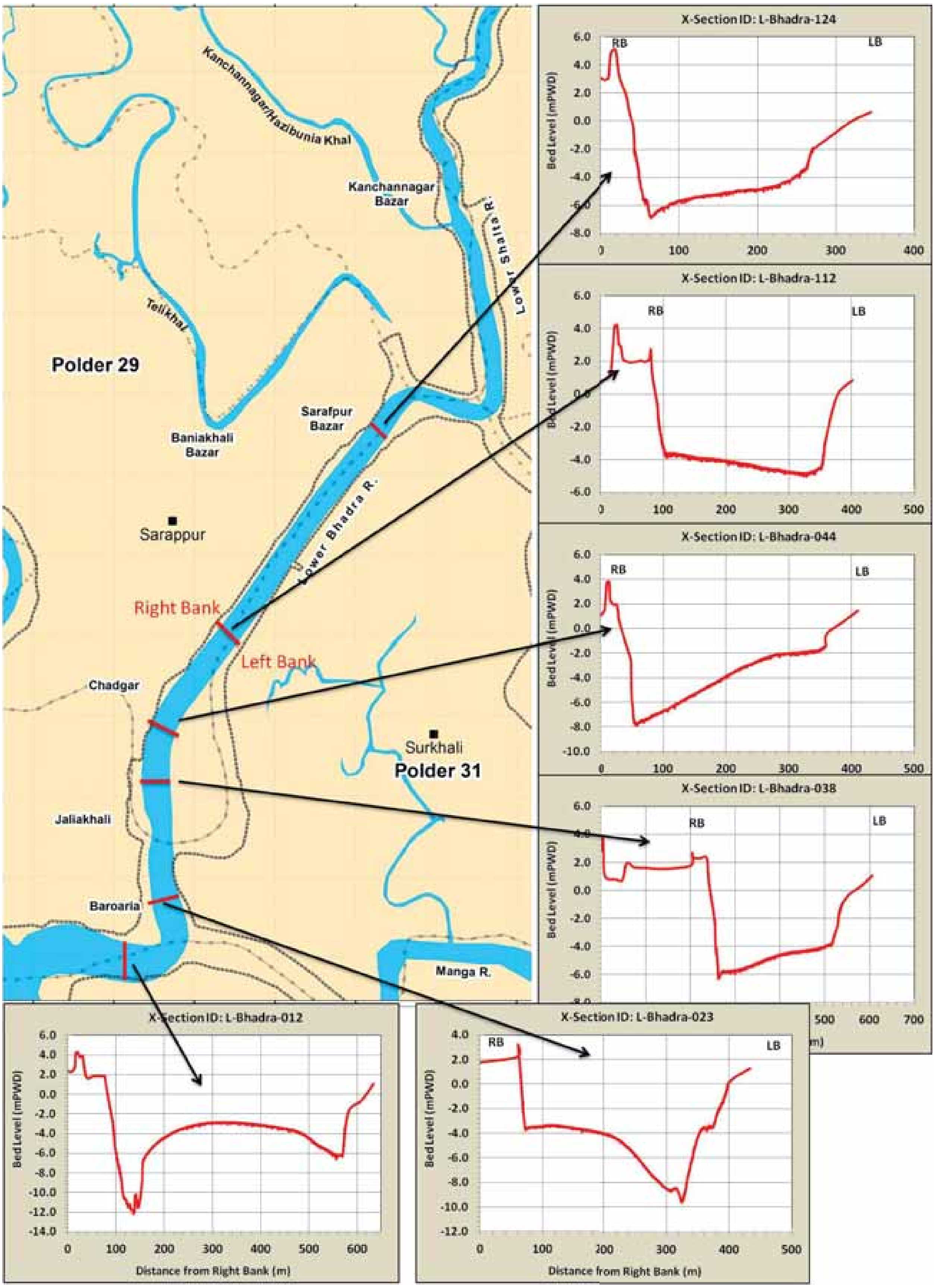

Figure 5-3: Selected cross-section profile of lower Bhadra River at different locations

5.2.2 Assessment of River Bank Line Shifting Characteristics by Satellite Image Analysis

The satellite images were digitized to make boundary between land and water. From these digitized geo-referenced Google Earth and Rapid Eye satellite images, the bank-line shifting i.e. the trend of erosion/accretion processes around the polders were assessed. The erosion/accretion for different years was determined at every 200 m interval along the chainage of peripheral embankment of the polder 29. It is mention worthy that the shifting of bank-line was measured perpendicular to the referenced line. From this information, the average yearly bank-line shifting was determined. Significant riverbank erosion is observed along this polder. Available satellite imageries of 2000, 2001, 2009, 2011 and 2015 were analyzed in order to estimate the erosion rate. The bank-line shifting of the polder from 2000 to 2015 is shown in Figure 5-4.

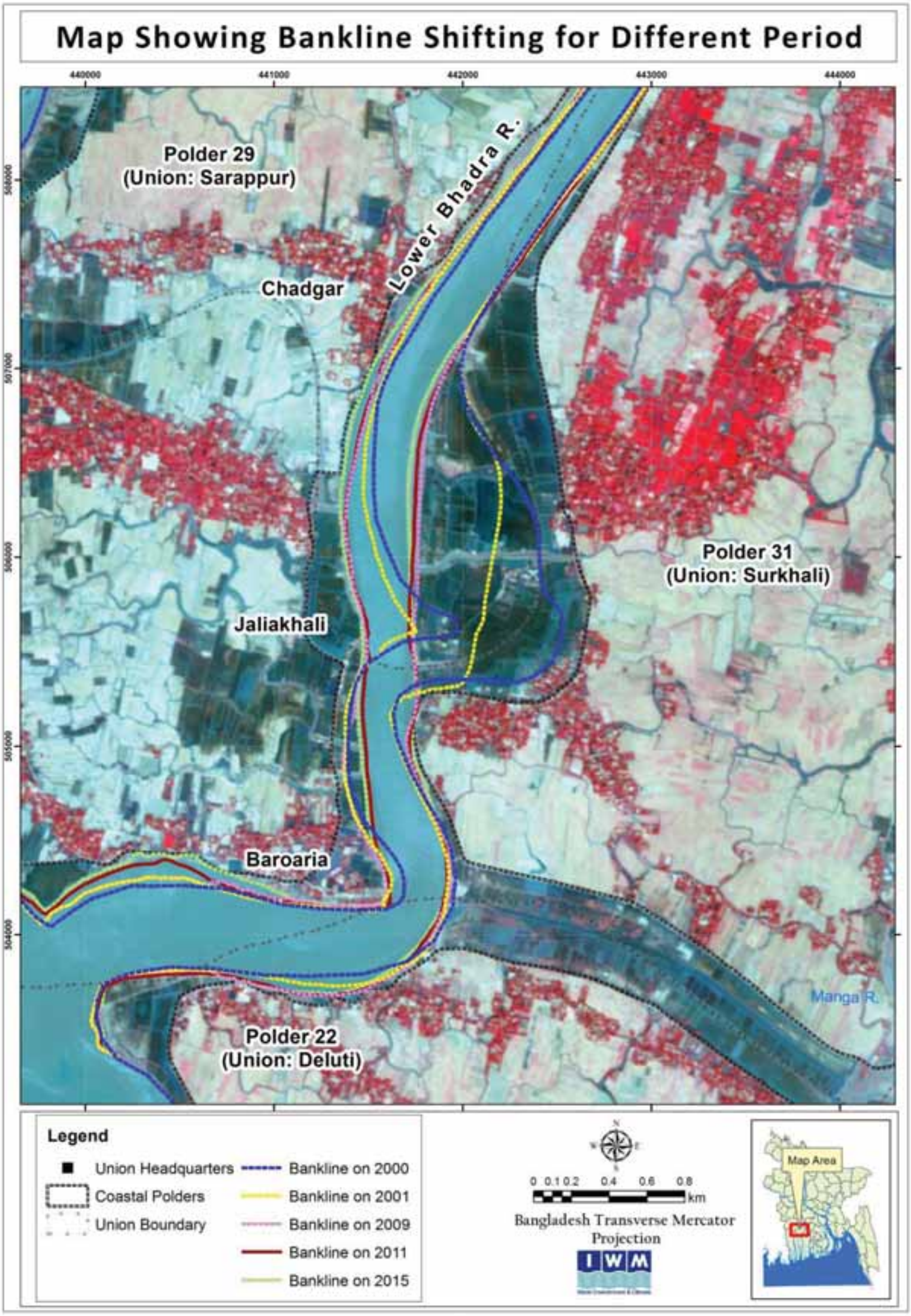

Figure 5-4: Map showing bank-line shifting from 2000 to 2015 period

From Jaliakhali to Chadgar along the 4.6 km length, the maximum bank erosion in Lower Bhadra River is about 60 m and average bank erosion is about 26 m during 2011 to 2015 period. Maximum bank erosion from 2011 to 2015 near Baroaria is about 70 m and average bank erosion along 1.88 km length is about 34 m in Lower Bhadra River.

5.2.3 Net Accretion-Erosion in the Project Area

Analysis of time series satellite images are used in identifying erosion prone areas and prediction of future erosion rates in the project area.

The study area is morphologically very dynamic. Figure 5-5 shows the eroded and accreted area from 2001-2009 near the study areas. Around the study area, erosion –accretion occurred simultaneously. Satellite image analysis shows that erosion is dominant along the right bank of Lower Bhadra River. Nearly 20.81 ha land was eroded away from 2001-2009 along the right bank of Lower Bhadra river as shown in the Figure. Total length of the eroding bank is about 3.9 km. On the other hand, huge accretion was occurred during this period along the left Bank. Approximately 66.61 ha land was accreted within 2.68 km river reach. Actuality during this period (2001-2009) river changed its course. Near Jaliakhali, there was a bend. During this period the bend became straight.

Table 5-1: Land erosion-accretion along the both banks of Lower Bhadra river 2001 to 2009

Lower Bhadra River	2001-2009	
	Left Bank	**Right Bank**
Erosion (ha)	8.38	20.81
Accretion (ha)	66.61	0.9
Length of eroded Bank (km)	2.39	3.90
Length of accreted Bank (km)	2.68	0.345
Rate of Erosion (ha/yr)	1.05	2.60
Average Erosion rate per km length of bank (ha/(km.yr)	0.44	0.67
Rate of Accretion (ha/yr)	8.33	0.11
Average Accretion rate per km length of bank (ha/(km.yr)	3.11	0.32

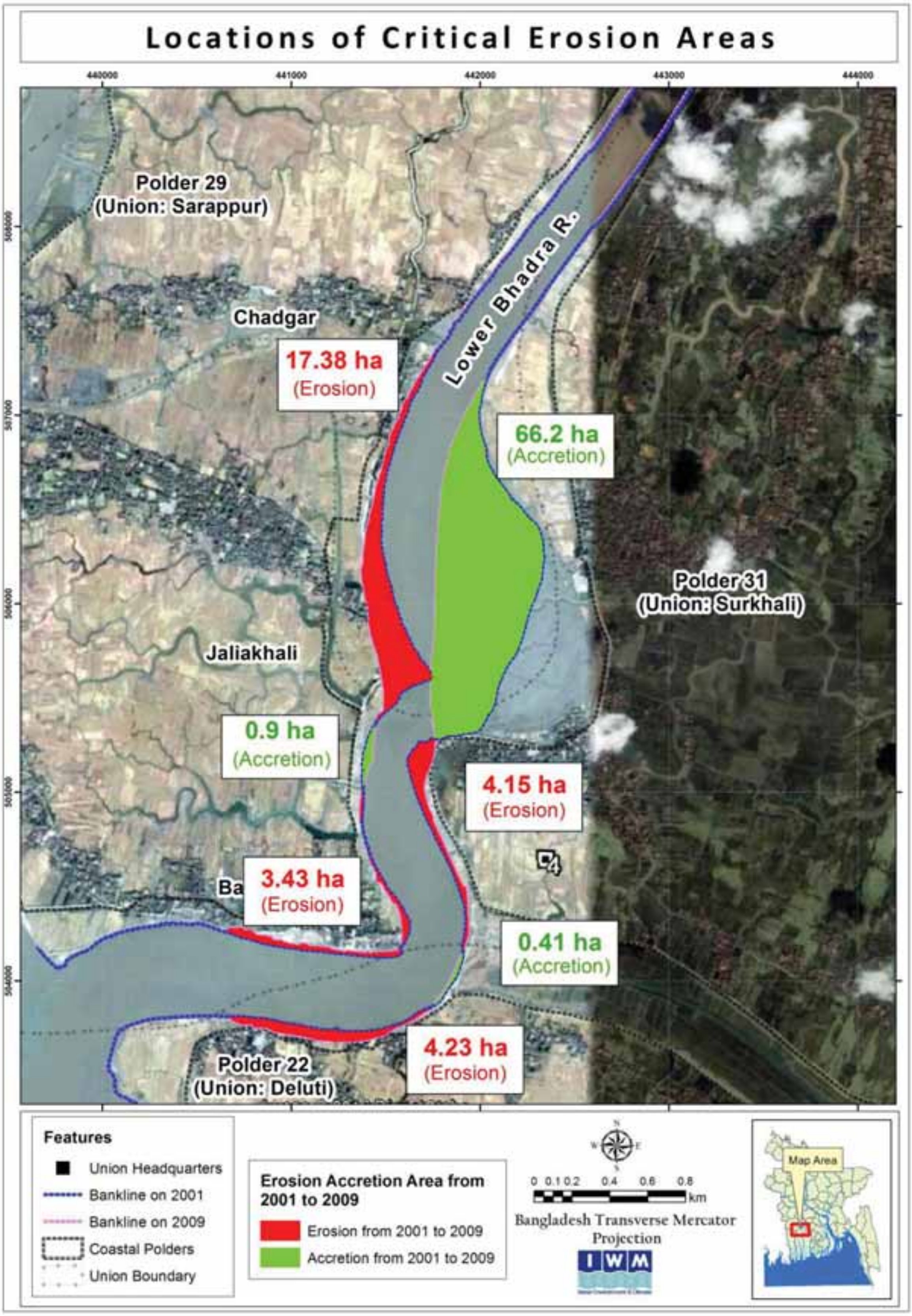

Figure 5-5: Eroded and accreted area from 2001-2009 along the both sides of Lower Bhadra river

Figure 5-6 shows the eroded and accreted area at both banks of the Lower Bhadra river over the period from 2009 to 2011. Erosion is prominent during this period at west of Baroaria Bazar only along the right bank. Total eroded area along right bank is 4.79 ha and length of eroding bank is about 0.86 km. No significant erosion occurred at Chadgar within this period. In addition, accretion occurred along the right bank. Total accreted river bank is about 2.44 km and accreted area is 9.34 ha.

Figure 5-6: Eroded and accreted area from 2009-2011 along the both sides of Lower Bhadra river

Figure 5-7 shows the eroded and accreted area at both the banks of the Lower Bhadra river over the period from 2011 to 2015. Erosion is prominent during this period along the entire length of right bank. Total eroded area along right bank is 18.10 ha and length of eroding bank is about 6.47 km. No accretion has occurred along the right bank during this period. On the other hand, there is considerable accretion on the left bank and accreted area is 5.9 ha within the accreted length of 2.76 km. It is clear from the image analysis that the river has been shifted towards west over the period.

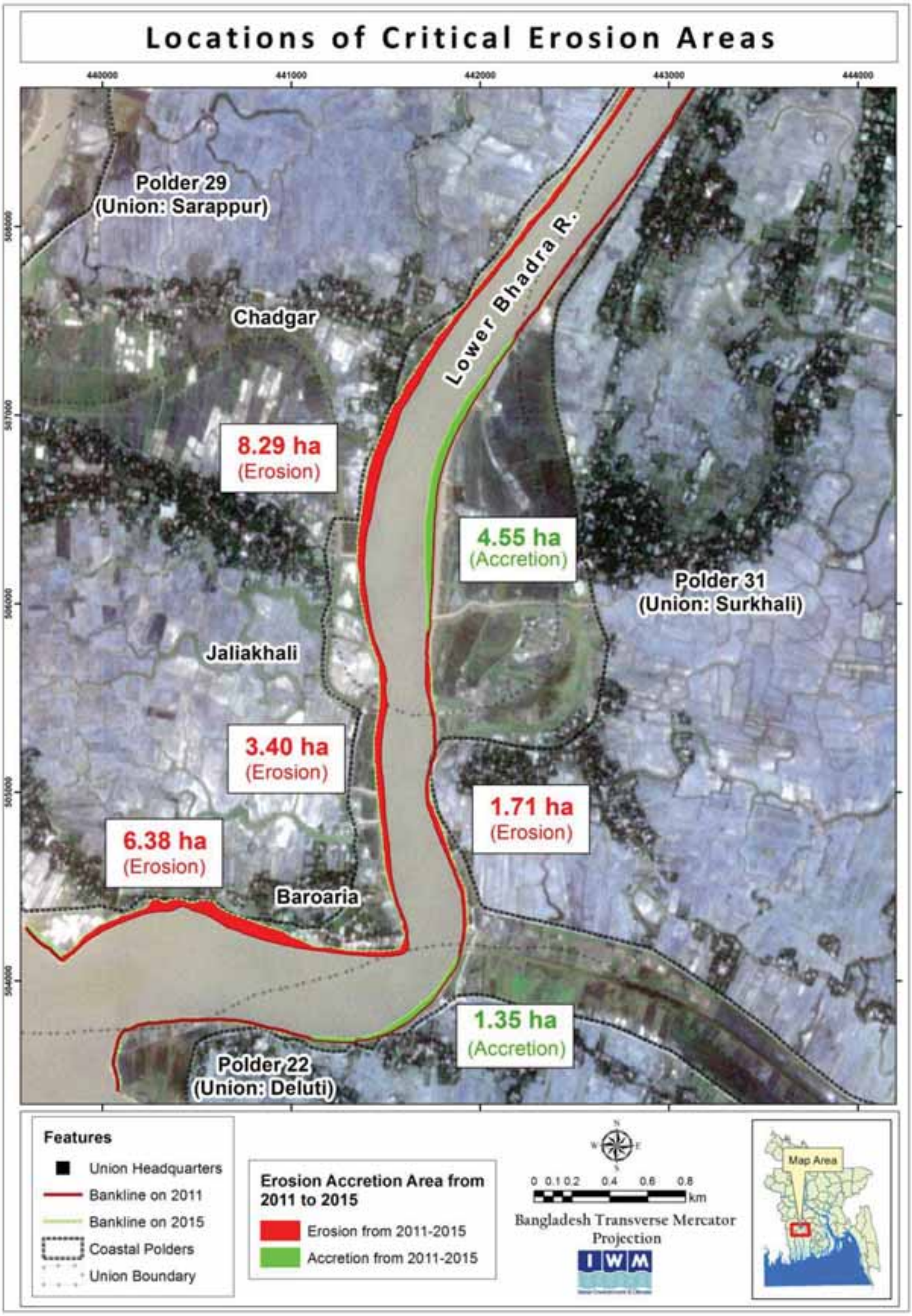

Figure 5-7: Eroded and accreted area from 2011-2015 along the both sides of Lower Bhadra river

Figure 5-8 shows total the eroded and accreted area near both side of the Lower Bhadra river over the period from 2009 to 2015. Erosion and accretion both are present during this period along the entire length of right bank. Total eroded area along right bank is 19.14 ha and length of eroding bank is about 4.81 km. Accretion has also been occurred along the right bank during this period. There is considerable accretion on the left bank and accreted river bank is about 3.19 km and accreted area is 9.69 ha. It is clear from the image analysis that the river shifted towards west over the period.

Figure 5-8: Eroded and accreted area from 2009-2015 along the both sides of Lower Bhadra river

Bank-erosion-accretion from the satellite images analysis (2009-2015) is given in Table 5-2.

Table 5-2: Bank-erosion-accretion history from 2009 -2015

Lower Bhadra River	2001-2009		2009-2011		2011-2015		2009-2015	
	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank	Left Bank	Right Bank
Erosion (ha)	8.38	20.81		4.79	1.71	18.10	1.02	19.14
Accretion (ha)	66.61	0.9	4.97	9.34	5.9		9.69	5.55
Length of eroded Bank (km)	2.39	3.90		0.86	1.55	6.47	0.60	4.81
Length of accreted Bank (km)	2.68	0.345	2.51	2.44	2.76		3.19	1.08
Rate of Erosion (ha/yr)	1.05	2.60		2.40	0.43	4.53	0.17	3.19
Average Erosion rate per km length of bank (ha/(km.yr)	0.44	0.67		2.78	0.28	0.70	0.28	0.66
Rate of Accretion (ha/yr)	8.33	0.11	2.49	4.67	1.48		1.62	0.93
Average Accretion rate per km length of bank (ha/(km.yr)	3.11	0.32	0.99	1.91	0.53		0.51	0.86

5.3 Identify Location of Scour Hole and Near Bank Erosion through Bathymetric Survey

The vulnerable locations of the project are considered at locations of deep scour hole, where the bank slope is much steep and has been experiencing huge current speed. Also position of thalweg line is considered to be an indicator in identifying location of potential bank erosion. If the thalweg line or location of deep scour hole is very close to the bankline, then this location is considered to be very susceptible for erosion. The thalweg lines in 2007 and 2015 are shown in the Figure 5-9. It is seen that the deep channel is gradually shifting closer to the right bank. Also scour has increased gradually near the erosion vulnerable area.

Figure 5-9 shows that from Jaliakhali to Chadgar, the thalweg line has been shifted towards right bank over the period and maximum shifting of thalweg line from 2007 to 2015 is about 207 m. Near Baroaria, thalweg line shifted more towards right bank and maximum shifting is about 327 m. Near Jaliakhali to Chadgar and Baroaria, the thalweg line is very close to bank-line and it is nearly coincides with the bank-line. It indicates that these areas are highly vulnerable to erosion.

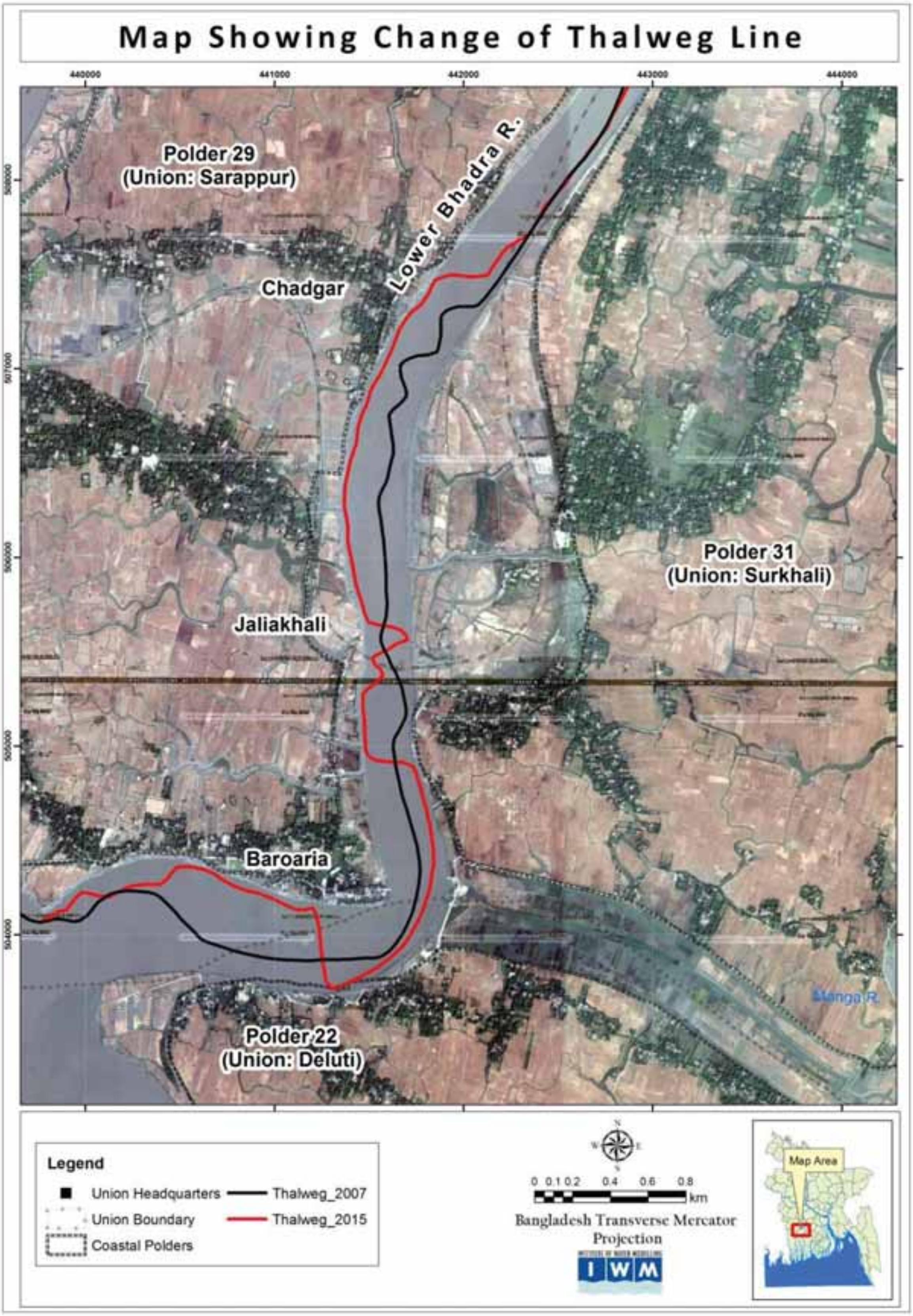

Figure 5-9: Shifting of Thalweg line from 2007 to 2015 in the Lower Bhadra river

5.4 Erosion vulnerable area and Extent of Bank Protection Works

The criteria for selecting erosion vulnerable area are:

- Near bank velocity
- Angle of attack
- Distance of thalweg line (deeper channel) from bank-line
- Locations of deep scour holes
- River bank slope

The vulnerable locations of the project are considered at locations of deep scour hole, where the bank slope is much steep and experiencing huge current speed. Also position of thalweg line (deeper channel) is considered to be an indicator in identifying location of potential bank erosion. If the thalweg line is very close to the bank-line, then this location is considered to be very susceptible for erosion. It is seen that the deep channel has approached very close to the bank-line near Chadgar, Jaliakhali and Baroaria. It indicates that river stretch here is in the process of very severe bank erosion. It is seen that a stretch of 1.63 km length of bank-line near Chadgar and 1.45 km length of bank-line near Baroaria are vulnerable to bank erosion. These areas need bank protection. The locations are shown in Figure 5-10. Although satellite image analysis from 2011-2015 shows that bank erosion is going on along the bank from Jaliakhali to the east of Baroaria, erosion protection measures is not suggested here. There is sufficient setback distance from bankline to embankment at this location. This portion is in dynamic equilibrium condition. It is seen from the satellite image analysis from 2009-2011 that huge accretion took place here but from 2011-2015 erosion occurred. Ultimately from 2009-2015 this area experienced net accretion. Erosion protection measure is not suggested here now but monitoring of bank-line stability has been recommended for future action.

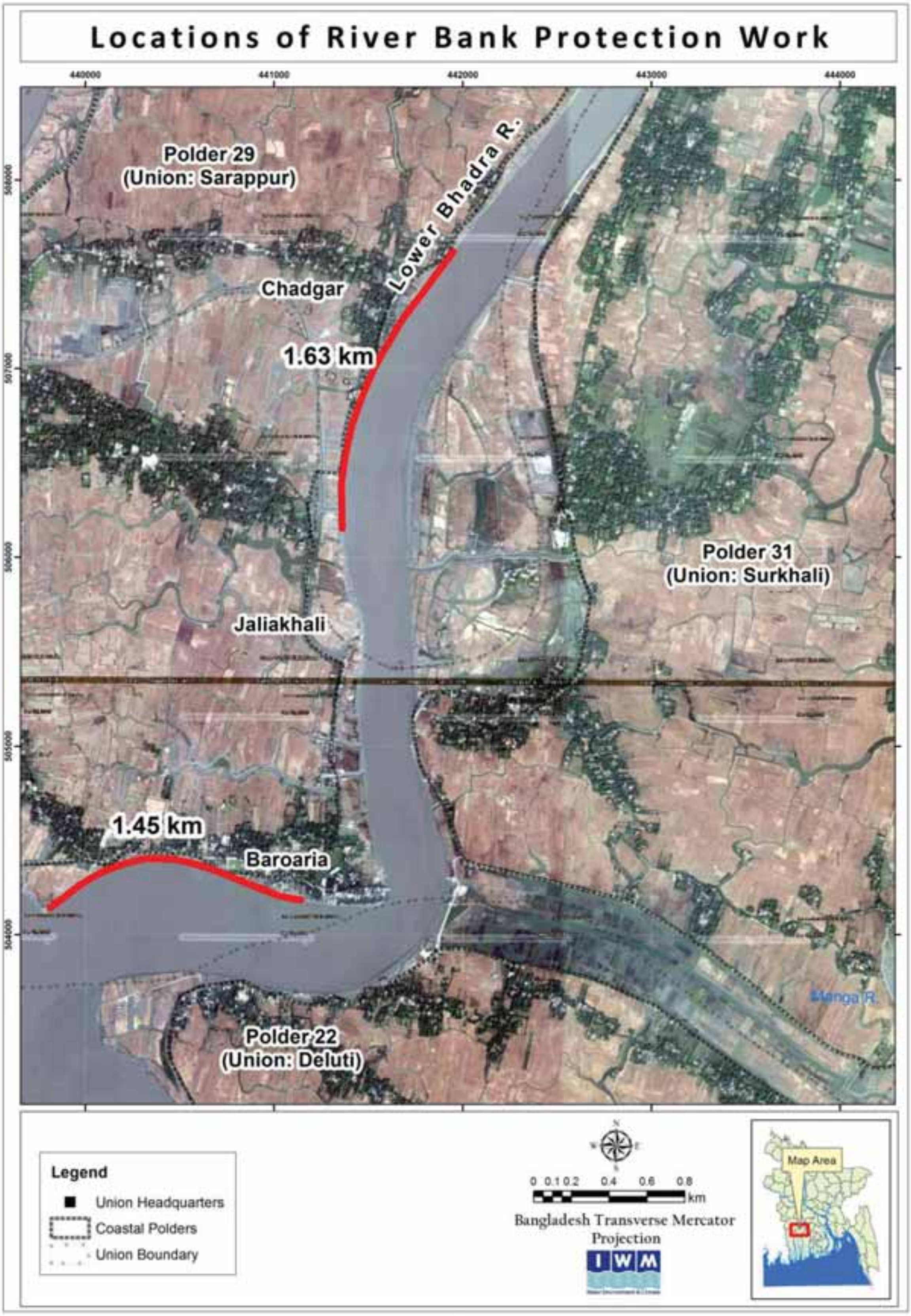

Figure 5-10: Proposed bank protection locations

6 SELECTION OF MITIGATION MEASURES AND ASSESSMENT OF EFFECTIVENESS

6.1 Selection of Mitigation Measures

Selection of alternative mitigation measures and final selection of bank protection measure needs to be cost-effective, sustainable against likely changed flow regime and morphological behaviour and acceptable from technical, environmental and social consideration. As such, to assess the effectiveness of potential measure, verification of all the bank potential measures has been carried out applying modelling. Maximum near bank velocity, erosion-deposition pattern, and changes of flow direction has been determined from model simulation results in order to identify effectiveness of the option. Considering all physical, environmental, social, economical and technical points, final option for implementation to protect the bank erosion has been selected. The following alternative measures have been investigated for river bank protection of the study area for selecting best suitable measures.

Bottom Vane:

Bottom vanes are vortex generating devices that are mounted on the river bed at an angle to the prevailing flow direction. The vanes are vertical foils installed in the channel bed in order to control sediment in the alluvial rivers. They can be used effectively for sediment management and training of alluvial rivers. The pressure difference between the pressure and suction sides of the vanes produces vortices that alter the transverse slope of the alluvial river bed in a zone downstream of the vanes. This is effective in changing velocity and depth distributions along river bend. It creates secondary circulation in the flow. The combination of vane induced circulation and stream-wise velocity causes a helical motion in the flow downstream from the vane. This helical motion creates a transverse shear stress to the river bed which results in sediment transport in the transverse direction. When a bottom vane is placed in a river bed at an small angle with the flow, sediment is picked up from the suction side and deposited to the pressure side. By installing arrays of vanes, sediment can be redistributed in a large reach.

The analytical and experimental studies conducted at The University of Iowa have lead to a concept for bank protection, and for control of riverbed degradation and aggradation. This concept involves use of specially designed vanes installed in particular arrays near the outside of the bend so as to divert the slower-moving bottom water toward the outer bank and thereby prevent undermining and high-velocity erosive attack on the outer bank. For aggradation and degradation control, the vanes are installed in rows, with particular orientations and in designed arrays, on either side of the channel thalweg. In both the cases, the vanes modify or generate secondary currents which reduce bank erosion and/or alleviate channel degradation or aggradation, depending on the design of the vane array. Bottom vanes were tried in the Meghna Estuary area in Bangladesh, but could not perform well because of the base erosion. This bottom vane can be applied for narrow channel. Besides there is a probability to loss of bottom vane due to monsoon flow or other reasons.

Porcupine:

Porcupine is another means to reduce the bank erosion. It traps the sediment and cause sedimentation near the bank. But there is a huge probability to be displaced the porcupine due to high magnitude of flow in monsoon and relocated in the deep channel. As a result, it loses its sedimentation capacity near the bank and becomes in-effective. Also from field observation and consultation with people, it is evident that the porcupine cannot trap sufficient amount of sediment that can stop bank erosion as per requirement.

Bamboo Bandalling:

Bandal is a traditional local structure mostly used in Indian Sub-Continent countries like India, Bangladesh etc. for improving and/or maintaining small navigation channels during lean period. Recently it is also practiced to block the secondary channels of the Ganges River in India. Bandals are temporary structures generally build to use for one season and is damaged or washed away during flood period. The structure is made of local materials like wooden log, bamboo etc. The specialty of this structure is that the top part is blocked and the bottom is open for passage of water. Its hydraulic functions are aimed at diverting the high velocity flow at the top and allow major suspended sediment laden lower velocity flow to pass at the bottom. The diverted flow causes degradation in the main channel. Bamboo mats are placed at the top for blockage of the flow. Several layers of closely spaced supports are used for the structural safety. The bamboo or wooden supports and struts of the bandals act as a roughness element to reduce velocity in the downstream direction, as a result sedimentation is possible at downstream of bandals.

The low cost bamboo bandalling structures are constructed at the river bank at a certain angles with water flow direction usually 30 to 40 degrees depending the flow intensity and stream power with the particular spacing such as 2 to 3 times of the bandals length. It was observed that water flow is diverted from the bank-line towards the mid-stream of the river due to Bandals.to reduce velocity near the bank resulting sediment deposition where bandals are placed. Stability of the bandling method is very poor. It is difficult to keep it at right position and during monsoon normally it is washed away. It can be shifted or stolen very easily. Although it is low cost, this cannot be mitigation measures for river bank protection of the Bhadra River.

Permeable Spur/Groyne:

Traditionally impermeable spurs, revetments etc. are used for stabilization purpose. In impermeable spur case flow concentration and separation is very strong at the spur heads. High concentration of velocity, bed shear stresses, vortices, down flows and turbulence at the upstream of spur head causes extremely large local scour holes around the spurs. Special toe protection is needed for these spurs. Impermeable spurs show good performance in formation of deeper main channel. Strong recirculating current comes back to the spur causing erosion in the spur fields and the bank. Spur field deposition and bank building is not so effective for this type of spurs. Closer spacing is required to ensure effective protection. Also, these hard type structures are now believed to cause environmental degradation. For this reason now permeable spurs are adopted as an alternate solution.

Permeable Spurs are the structures extended from the riverbank into the river. There is a preferred angle between the spur and the bank depending on the purpose of the spur. A series of permeable spurs in a longer straight reach can also create flow concentration & separation and similar main channel like impermeable spurs, with more uniform cross section. Spacing equalizing one time of the spur length is sufficient for bank protection in permeable case. Absence of dead water zone would ensure pollutant removal and better river ecology in the case of permeable spur. The flood resistance and flood duration would be less for permeable spurs. Because of the less main channel degradation, permeable spurs can be used for the rivers having much less sediment flow, to maintain the main channel bed level within an allowable range of scour/deposition. Permeable spurs can effectively be used for river course stabilization and restoration of river to adequate natural conditions, as now being tried in Europe and North America). Due to much less local scour around spur heads the toe protection cost will be less for permeable case.

Hydrodynamic condition has been simulated including series of permeable spur along the erosion vulnerable bank. Model simulation result shows sufficient reduction of velocity which can effectively reduce bank erosion. Permeable spur can be constructed with wooden pile (Shal-Bullah). Generally spurs are used to divert the river flow away from the critical zones of bank to protect it from the erosive action of the river. Series of permeable spurs has been selected as erosion mitigation measure.

Protrusion length of the semi permeable spur determined by distance between river bank to the local scour hole. The reason to limit the protrusion length of spur up to the scour hole is to minimise the length of spur pile. For example, elongation of a typical spur placed at -12 mPWD (Figure 5-3) is 20 meter. Here, length of a wooden pile is 15 meter [(12+3) meter]. Hence for 5 meter embedment, 20 meter wooden pile is required. Installation of 20 meter wooden pile with joint is difficult in the field.

Local scour hole beyond the groyne system is to be filled with sand-filled geo-bags. The level of geo-bag filling is adjusted from the bathymetric survey to minimize the bank erosion and to reduce the vulnerability of furthest pile in a spur system.

Maximum protrusion length is limited by 50 meter. The spacing of permeable spurs along the river is 2.5L, where L is the protrusion length of the permeable spur. Spacing varies based on the protrusion length of the permeable spurs.

In order to avoid or minimize the scouring around the bottom of the wooden pile, dumping of brick bats is suggested.

Some studies have shown that there is considerable reduction in maximum scour depth for permeable spur dikes when compares to those in the corresponding impermeable spur dike situations.

6.2 Specification and Spacing of Permeable Spur

Series of semi-permeable spur has been adopted in river hydraulic condition simulation. Semi-permeable spur has been considered along 1.63 km length near Chadgar and 1.45 km near Baroaria (Figure 5-7) along the right bank of Lower Bhadra river. The spacing of the semi-permeable spur varies from 65-125 m in Chadgar and 70-140 m in Baroaria. The protrusion length of each spur varies from 25-50 m at Chadgar and 20 – 50 m at Baroaria.

Blockage in a spur is 40%-50%. The semi-permeable spur would be constructed by wooden piles. The diameter of each pile is 0.2 m (6-8 inch). As the protrusion length varies, the number and length of wooden piles also vary from spur to spur. The semi-permeable spurs are placed at right angle at 40^0 angle and at 60^0 angle to the bank-line to see the effectiveness for different orientation and select the suitable orientation. The Lower Bhadra River is a tidal river. If the semi-permeable spurs are at right angle to the bank, the thrust is maximum at the upper and lower spurs during ebb and flood tide respectively. But if the spurs are at an angle with river bank, the thrust will be reduced significantly. Orientation of the spurs with 60^0 angle has been selected for the final design and shown in Figure 6-1 and Figure 6-2.

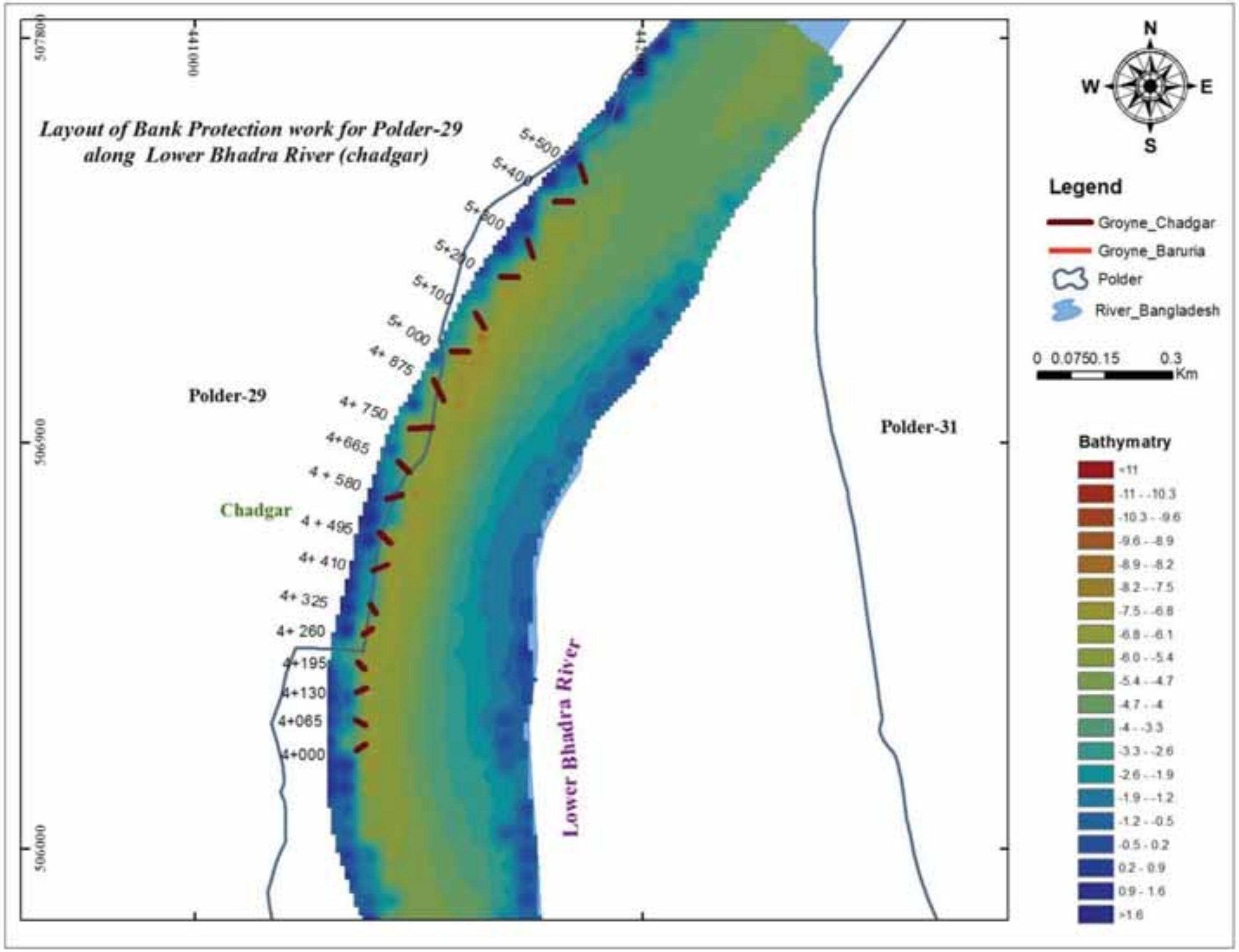

Figure 6-1: Proposed permeable spur location and orientation near Chadgar

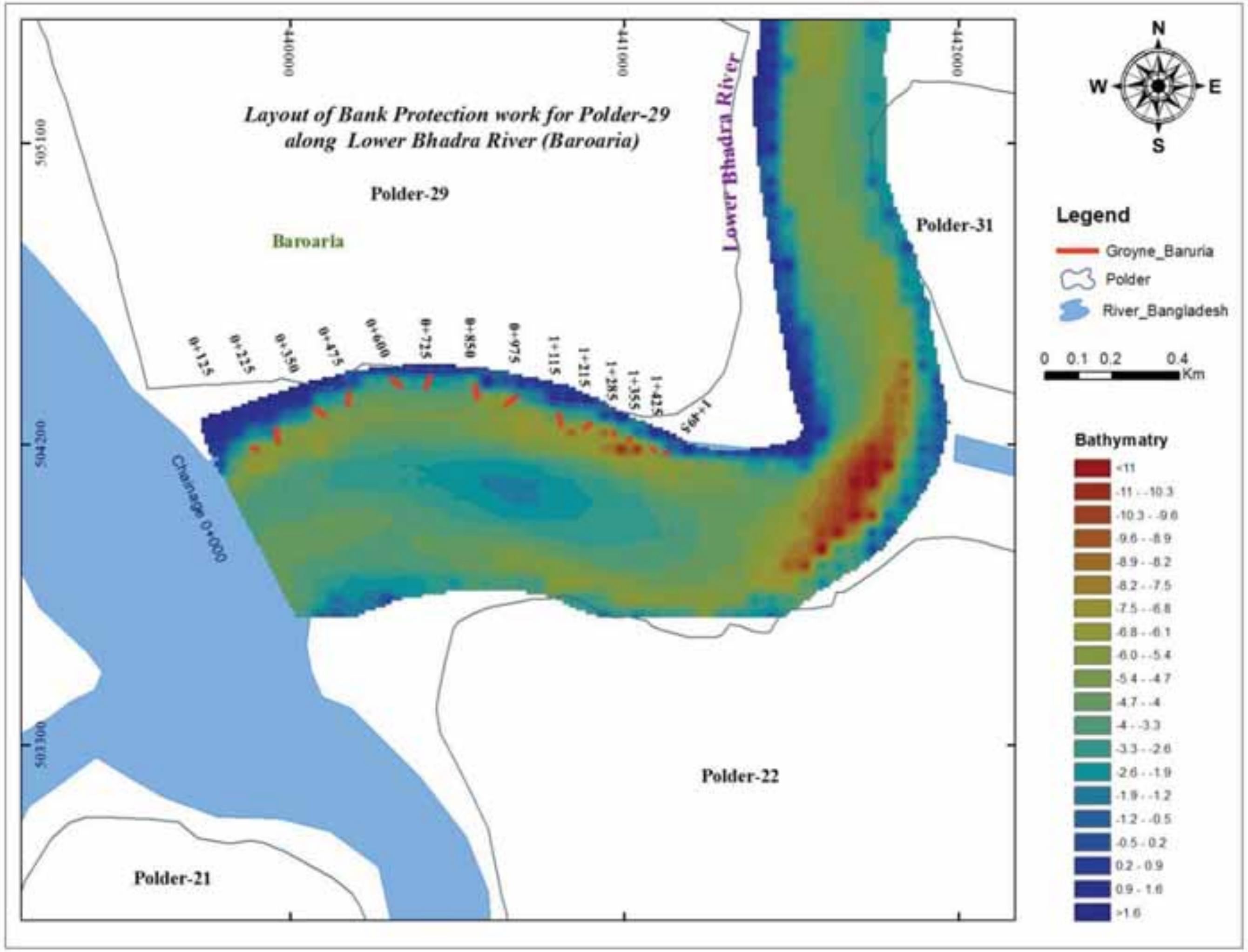

Figure 6-2: Proposed permeable spur location and orientation near Baroaria

6.3 Assessment of Effectiveness

The effectiveness of permeable spur has been assessed by simulation of different flow condition. River hydraulic condition has been simulated in dry and monsoon period considering the permeable spurs. The results showed positive response in the erosion reduction process with permeable spurs. Reduction of current speed and sediment deposition along the erosion vulnerable area are evident. Current speed which is considered to be one of the prime factors for erosion propagation is reduced significantly with permeable spurs. Simulation results with and without permeable spur for dry and monsoon period perpendicular to the bank-line and with 60^0 to the bank-line are given below.

Permeable spur perpendicular to the bank-line

Figure 6-3 and
Figure 6-4 show the comparison of current speed between with and without permeable spur in monsoon and dry period for 2012. Here permeable spur is located perpendicular to the bank-line.

Maximum depth averaged current speed during monsoon period varies from 2.75 m/s to 1.5 m/s along the right bank of Lower Bhadra river at Chadgar without permeable spur. But with permeable spur the velocity is reduced considerably along the right bank-line and it becomes 1.50 m/s to 0.75 m/s. The average reduction of current speed is about 30% in that area.

Velocity reduction is more near Baroaria. Without permeable spur, the maximum depth average current speed varies from 1.50 m/s to 0.75 m/s but with permeable spur the maximum depth average velocity varies from 0.90 m/s to 0.61 m/s. Reduction of current speed is also about 30% here.

During dry period current speed is less and at this time bank erosion doesn’t takes place. In dry period, current speed also reduced significantly with permeable spur.

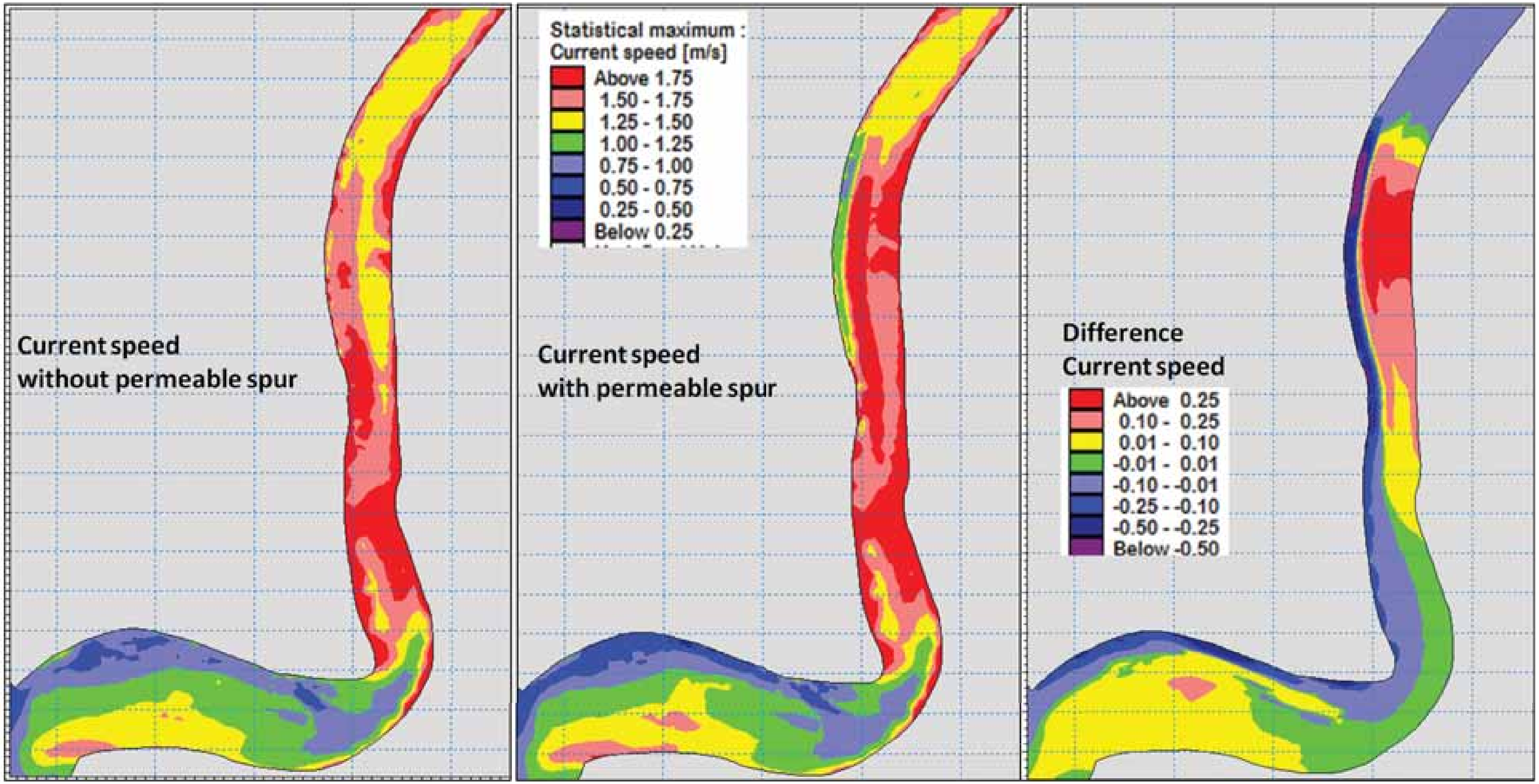

Figure 6-3: Maximum current speed and difference of maximum current speed without and with permeable spur in monsoon period making right angle to the bank-line

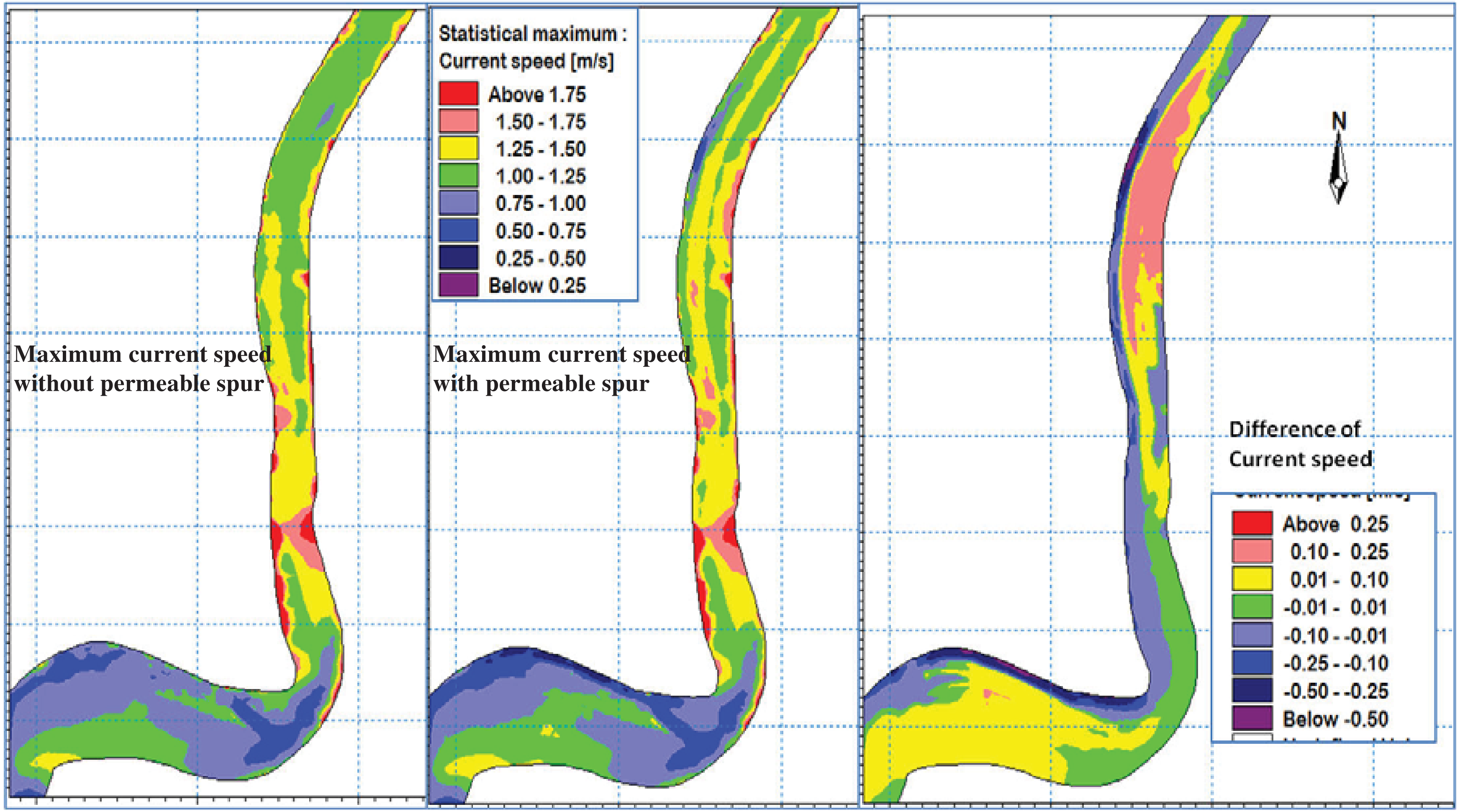

Figure 6-4: Maximum current speed and difference of maximum current speed without and with permeable spur in dry period making right angle to the bank-line

Permeable spur/spur making angle 60^0 to the bank-line

Figure 6-5 and Figure 6-6 show the comparison of current speed between with and without permeable spur in monsoon and dry period for 2012. Here permeable spur is located at 60^0 angle to the bank-line.

Simulation results show that current speed reduction is more with permeable spur making an angle 60^0 to the bank-line. Average current speed reduction is more than 35% near Chadgar. Also Maximum velocity varies 1.50 m/s to 0.64 m/s along the bank-line. Here another advantage is that spurs at upstream and downstream side face less thrust which is favorable for stability of the spur. Also flow separation is strong here.

In dry period velocity reduction is more with 60^0 angle to the bank-line. It is clear that permeable groyne/spur is more effective and preferable making an angle 60^0 to the bank-line compared to perpendicular to the bank-line.

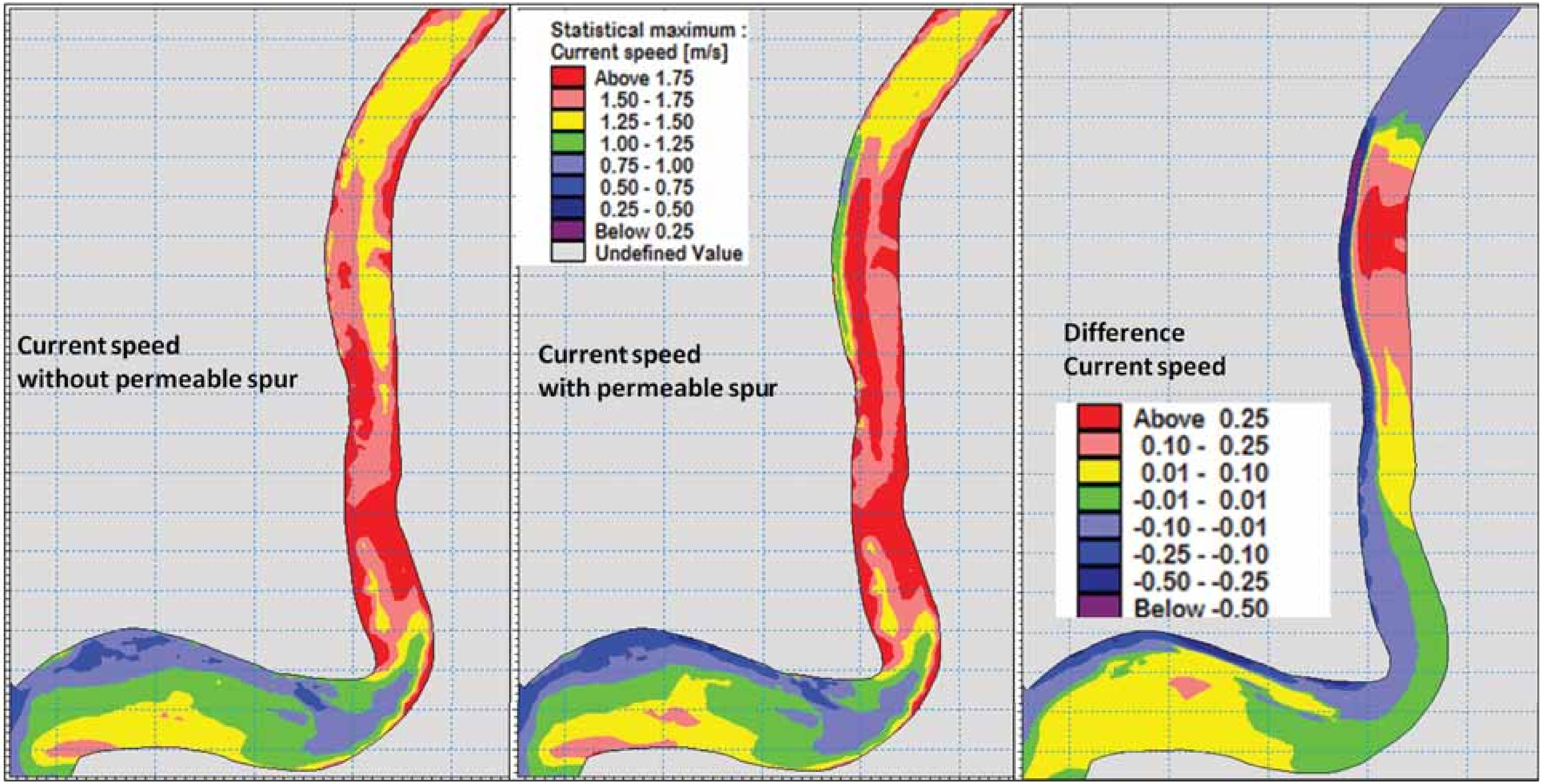

Figure 6-5: Maximum current speed and difference of maximum current speed without and with permeable spur in monsoon period making angle 60^0 to the bank-line

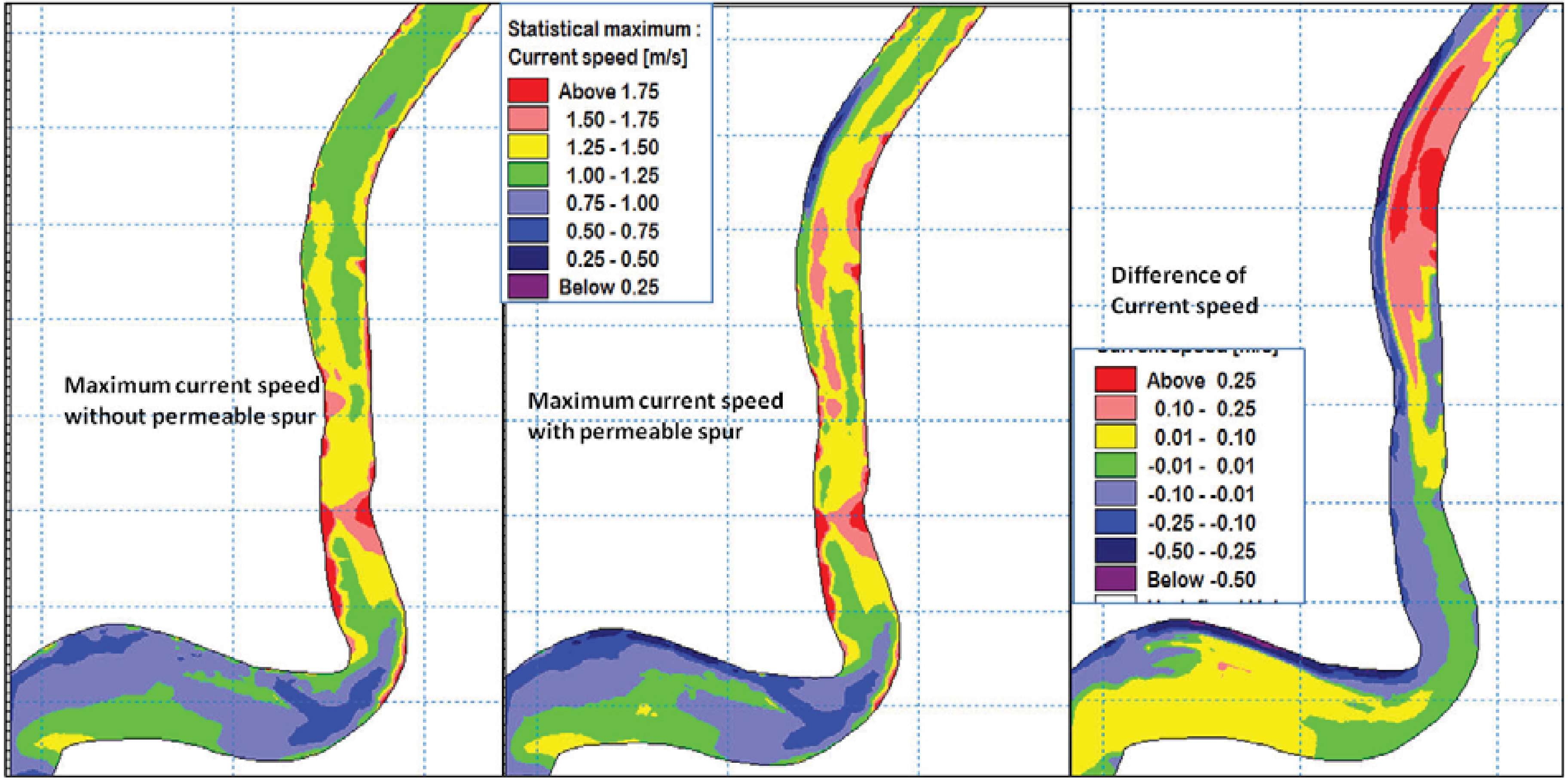

Figure 6-6: Maximum current speed and difference of maximum current speed without and with permeable spur in dry period making angle 60^0 to the bankline

6.4 Morphological Modelling Results

A morphological model has been developed incorporating semi-permeable spur for the study area. But it could not be properly calibrated due to unavailability of quality data. The model is rather an indication of the morphology of the study area after implementing semi-permeable spur. Figure 6-7 shows the existing bed level and bed level after monsoon from morphological model simulation with permeable spur. The morphological model shows that the spurs accelerates sedimentation and divert the flow away from river bank shown in Figure 6-7.

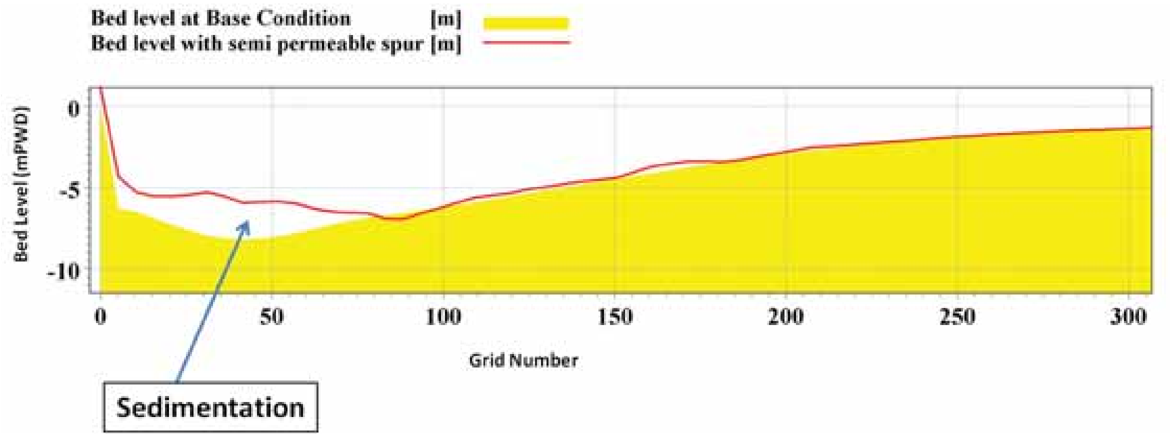

Figure 6-7: Semi-permeable spur accelerates sedimentation at the river bank

6.5 Practice of Bank Protection Works in Bangladesh

The river erosion mitigation measures widely practiced mainly include three types i.e. revetment, hard-point and spur (or groyne). Among them, bank revetment is widely used in Bangladesh. Revetment protects the river bank directly from the erosive forces such as current or waves or both. The erosion protection of riverbank by revetment is expensive because the same construction is required to be implemented all along the river bank under active erosion in deep water and scour hole. Construction of series of groyne protruding from river bank will be very hazardous due to fluctuation of tidal water and also deep water. Further, unless a series of groynes are constructed simultaneously, no/minimum benefit is expected. Moreover, past experience on the stability of groynes is not satisfactory. Construction of hard-point and revetment on the other hand is less complicated as the same are usually constructed on the river bank. Hard-points are constructed for protecting certain infrastructure or important place of business centre leaving the other areas on both upstream and downstream to allow bank migration on the agricultural land.

6.6 Option considered for cost analysis

For cost analysis, three different bank protection measures have considered for bank protection measures. The considered options are

1. Semi-permeable spur from riverbank up to scour hole + sand-filled Geo-bag dumping at scour hole.
2. Slope protection with CC block + Geo-bag dumping at scour hole.
3. Semi-permeable spur from river bank up to scour hole.

All these options are shown in Figure 6-14, Figure 6-15 and Figure 6-16

6.7 Design Parameters for bank protection works

Hydraulic Characteristics of Lower Bhadra River near the study area is given in Table 6-1.

Table 6-1: Design parameters for mitigation measure

Data	Value	Source
Discharge (m^3/s)	2546 – 3137	Model Results
High Water Level (m PWD)	3.75	Model Results
Low Water Level (m PWD)	-1.87	Model Results
Maximum Depth Average Velocity (m/s)	1.02 – 3.00	Model Results
Near bank Thalweg Level (m PWD)	-7.84 to -12.76	Surveyed in 2015
Average diameter (d50) of bed material, dm (mm)	0.175	Surveyed in 2015
Significant wave height, Hs (m)	0.11	
Peak Wave period, Tp (s)	1.03	

6.8 Design and cost estimates of selected mitigation measures

6.8.1 Selection of Alternative

The design of the bank protection works has been prepared on the basis of model generated data/measured data such as water level, water flow, flow velocity, scour depth and design methodology according to available Manual and Standard.

Cost analysis has been performed for three different bank protection measures to protect the erosion vulnerable area. They are as follows:

1. Semi-permeable spur up to scour hole + sand filled Geo-bag dumping at scour hole.
2. Slope protection with CC block + sand filled Geo-bag dumping at scour hole.
3. Semi-permeable spur from river bank up to scour hole.

OPTION-1: SEMI-PERMEABLE TIMBER SPUR + GEOBAG DUMPING

In this option, semi-permeable spur has been considered making an angle 60^0 with the bank-line. Each spur has double layer of wooden piles. Diameter of each pile is 6-8 inch (0.20 m). Pile spacing is 16 inch (0.40 m). Spacing of each layer is 0.60 m. The length of the permeable spur varies at different locations based on scour hole. Sand-filled geo-bag will be dumped in the scour hole and the semi-permeable timber spur will be provided up to the starting of scour hole. Brick bats are recommended around the bottom of permeable spur.

It is recommended to tie the whole length of the permeable spur by a pair of horizontal wooden piles perpendicular to the bank line. One wooden pile is recommended 3 m below from top of the permeable spur and another pile is recommended 3 m above from the bed level. Each of the two horizontal "tie piles" should be fixed firmly with the vertical member of a spur with G.I nut-bolts /screws through a hole drilled at the crossing of the horizontal and the vertical wooden piles of a spur) to act as a monolithic member.

Near Chadgar and Baroaria, the thalweg line has been coincided to the bank-line of Lower Bhadra river. At Baroaria bazar, the lowest bed level varies between -11 to -13 mPWD. The height of timber spur could reach from 19 to 21 m, which is not feasible in terms of structural stability and costing. As a result, sand filled geo-bag was selected to be dumped in the scour hole at levels from -8.0 to -5.0 mPWD depending on the bed/slope position of the scour hole and the semi-permeable timber spur will be provided upto the starting of scour hole from the bankline. The scour holes have been investigated from the measured cross section. The design water level has been selected as the mean high water spring (MHWS) level at Lower Bhadra river which is 3.00 mPWD. The Embedment length of the piles has been calculated considering current induced load, wave induced load and floating debris. The schematic design of this option is as follows:

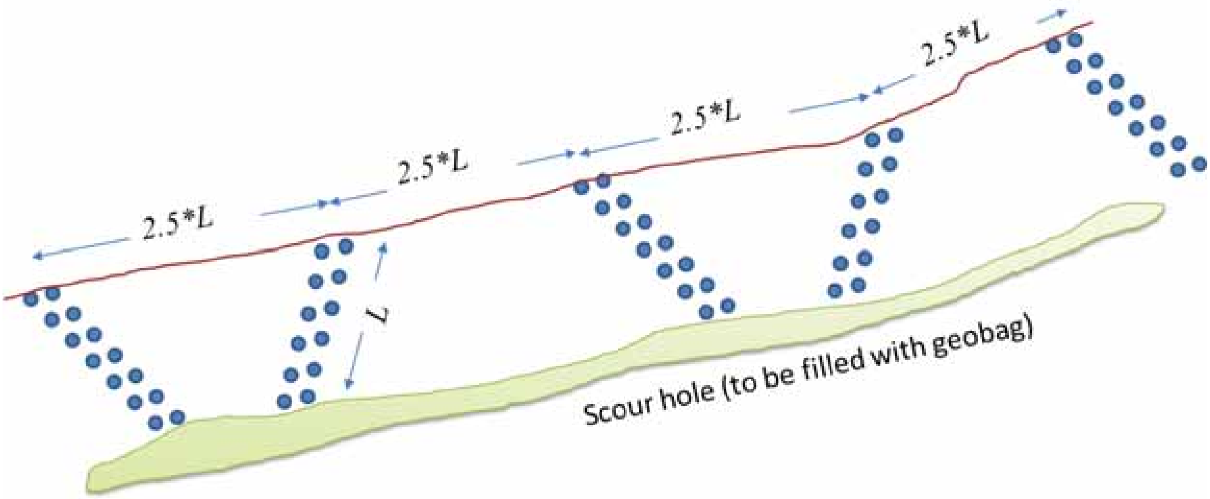

Figure 6-8: Schematic design of Option-1

6.8.2 Design of embedment for piles of semi permeable groyne

An individual pile of semi permeable groyne system has to resist the following loads:

1. Current induced load
2. Wave induced load
3. Floating Debris

Depending on the magnitude of the load the pile embedment is calculated. However, requirement of pile embedment is may vary from plate to place and it is mainly varied with depth of flow, current speed, significant wave height and floating debris height etc.

Pile embedment calculation is shown for typical location which is situated at Baroaria Bazar. The pile is located 1355 meter inward from the confluence of Lower Bhadra River and Gangreil River and it is located 23 meter away from the bank.

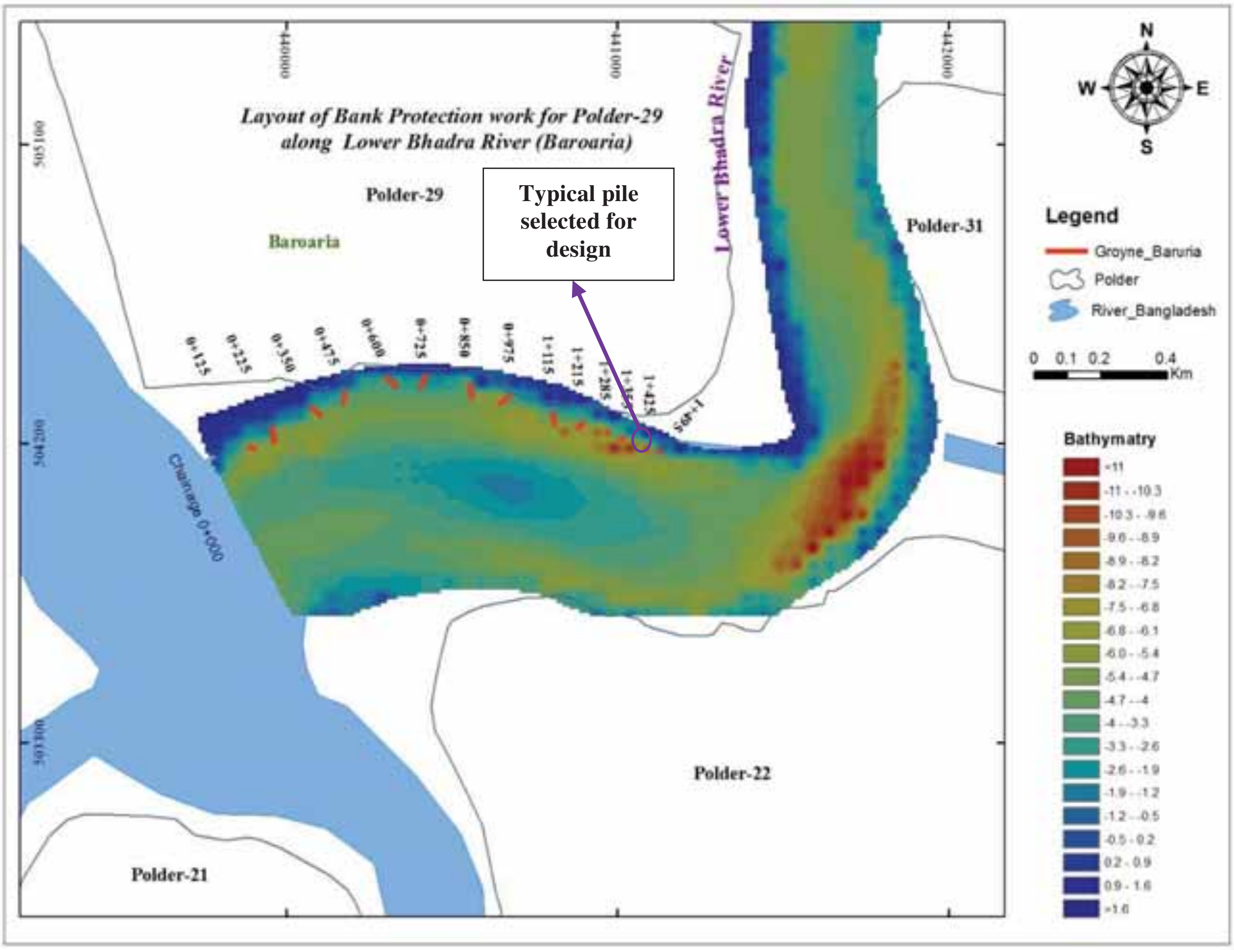

Figure 6-9: Layout of Groyne system at Baroaria.

In that particular location Maximum water depth is 8.8 meter. Current and wave induced forces and floating debris load calculation are presented below:

Current induced load

The single pile has to withstand forces resulting from flowing water. Due to the effect of the groyne, the flow velocities are reduced along the groyne axis towards the embankment.

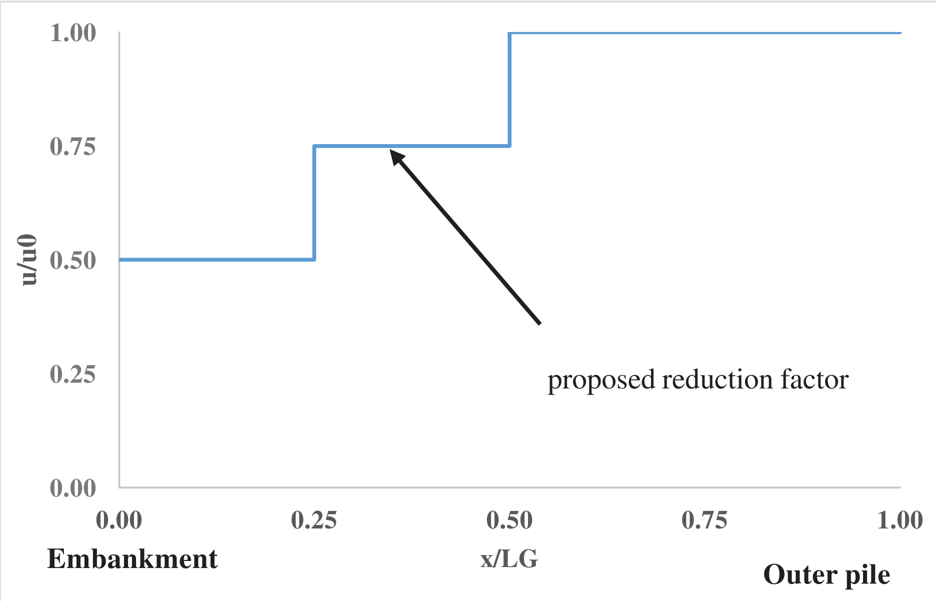

Figure 6-10: Reduction of flow velocities along groyne axis (recommended)

The Current induced load on a single pile can be determined by a momentum approach, based on the velocity distribution over the water depth:

$$P(z) = \int_{z=0}^{z=h} C_D . 0.5 . \frac{\gamma_w}{g} . D . u^2(z) . dz \quad \dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Here,

C_D =drag coefficient (C_D = 0.7 for circular piles)

γ_w = density of water = 9.8 kN/m^3

Pile diameter = 0.20 meter (8 inch)

u_1 (z) = depth dependent flow velocity (estimated from equation. 2)

D = Pipe diameter

u(z) = velocity

$$u \quad (z) = u_1 . \frac{\ln\left(30 . \frac{d_1 - z}{k_s}\right)}{\ln\left(11 . \frac{d_1}{k_s}\right)} \dots\dots\dots\dots\dots\dots \quad (2)$$

Here,

u_1 =average flow velocity (m/s) = 1.2 m/s

k_S = co-efficient of roughness of river bed = 0.017 (obtained bed roughness from calibrated southwest regional model)

$$\text{Velocity adjustment factor} = \frac{observed\ max^m\ velocity}{maximum\ u \quad (z)} = 1.34$$

$$\text{Adjusted velocity} = \frac{observed\ max^m\ velocity}{maximum\ u_1(z)} * \text{u} \quad (\text{z}) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

Table 6-2: Generated Velocity Profile.

Depth, z (meter)	**Velocity (m/s) u(z)**	**Adjusted Velocity profile from observation (equation 3)**
0	1.34	1.80
0.725	1.33	1.78
1.45	1.31	1.77
2.175	1.30	1.75
2.9	1.28	1.73
3.625	1.27	1.70
4.35	1.24	1.67
5.075	1.22	1.64
5.8	1.19	1.60
6.525	1.15	1.55
7.25	1.10	1.48
7.975	1.01	1.36
8.7	0.72	0.96
8.75	0.62	0.84

Table 6-3: Depth wise Current force distribution along cantilever wooden pile

Depth of water (meter) z	Velocity (m/s) u_1 (z)	Current Force (kN/m) Calc. from eq^{n}1	Current Force (kN) Calc. from eq^{n}1	Moment (kN.m)
8.8	1.80	0.23		2.00
8.075	1.78	0.22	0.16	1.80
7.35	1.77	0.22	0.16	1.61
6.625	1.75	0.21	0.16	1.42
5.9	1.73	0.21	0.15	1.23
5.175	1.70	0.20	0.15	1.05
4.45	1.67	0.20	0.14	0.87
3.725	1.64	0.19	0.14	0.70
3	1.60	0.18	0.13	0.54
2.275	1.55	0.17	0.13	0.38
1.55	1.48	0.15	0.12	0.24
0.825	1.36	0.13	0.10	0.11
0.1	0.96	0.07	0.07	0.01
0.05	0.84	0.05	0.00	0.00

Summation of force = 1.65 kN

Summation of moment = 12.20 kN.m

Moment arm, z_{sc} = 12.20/1.65 = 7.40 m

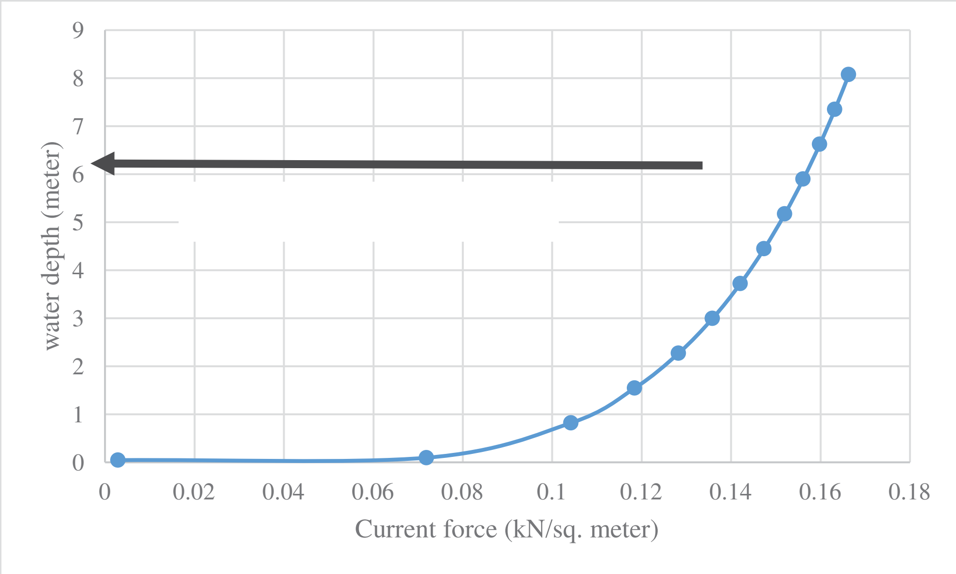

Figure 6-11: variation of current force along depth

Wave induce load

The wave induced load resulting from progressive waves consists of drag forces due to velocity components and inertia forces which are generated by acceleration components of orbital motion.

$$P(z) = P_D(z) + P_M(z) = \beta\left(C_D.\frac{1}{2}.\frac{\gamma_w}{g}.D.u(z).|u(z)| + C_M.\frac{\gamma_w}{g}.\frac{D^2.\pi}{4}.\frac{du(z)}{dt}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Phase velocity of wave, u

$$u = \frac{H}{2}.\omega.e^{k.z}.\cos\vartheta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\frac{du}{dt} = \frac{H}{2}.\omega^2.e^{kz}.\sin\vartheta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

However, wave velocity and wave acceleration will not be maximum at the same time, though the value of cosυ and sinυ is set to 1.0

Using the Morrison's equation (eq. 4)

Wave characteristics at that particular location is provided below:

Peak wave period (T) =1.03 s

Wave Height, H = 0.11 meter

Wave frequency, $\omega = \frac{2\pi}{T}$= 6.10 s^{-1}

Inertia Co-efficient, C_M = 2.0 (for circular pile) e = center to center distance between two pile = 16 inch

Relative spacing, e/D = 2

β = correction factor for narrow spaced pile = 1.50; [from table 3]

H = significant wave height

Wave length, $L = gT^2/2\pi = 1.65$ meter

Wave number, $k = 2\pi/L = 6.10\ s^{-1}$

Table 6-4: Correction factor β for different relative spacing e/D

e/D	1	2	3	4
P [%]	50	67	75	80
β	1.85	1.5	1.25	1.0

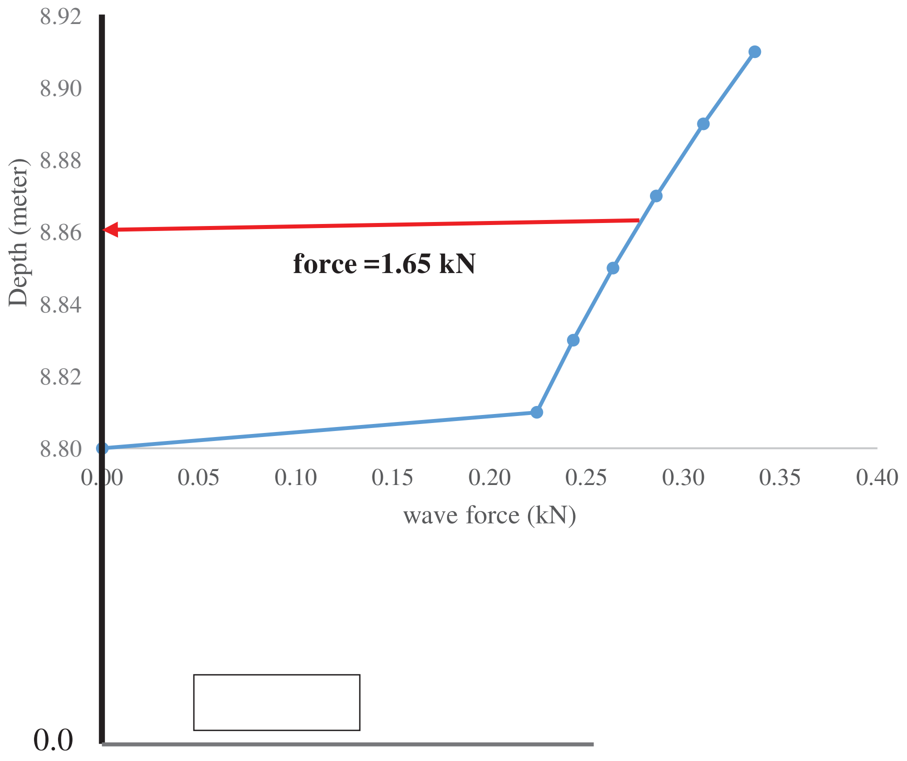

Figure 6-12: Wave force distribution along depth

Table 6-5: Depth wise wave force distribution on a wooden pile at High water level (=3.20 mPWD)

Vertical Depth from still water (above), meter	**wave velocity, u (m/s)** $u(z) = \frac{H}{2} * \omega * e^{kz} * \cos\upsilon$	**wave acceleration (m/s^2)** $\frac{du}{dt} = \frac{H}{2} * \omega^2 * e^{kz} * \sin\upsilon$	**I nertia force, kN (P_D)** $\left(C_{M.} \frac{\gamma_w}{g} . \frac{D^2 . \pi}{4} . \frac{du}{}\right.$	**Drag force, kN (P_M)** $\left(C_D . \frac{1}{2} . \frac{\gamma_w}{g} . D . u(z) . \lvert u\right.$	**Factored total force, kN (P_D+P_M)**	**Overturning moment (kN.m)**
0.11	0.51	3.11	0.21	0.019	0.34	3.00
0.09	0.47	2.88	0.19	0.016	0.21	1.84
0.07	0.44	2.67	0.18	0.014	0.72	6.42
0.05	0.41	2.47	0.16	0.012	0.04	0.32
0.03	0.38	2.29	0.15	0.010	1.43	12.59
0.01	0.35	2.13	0.14	0.009	0.00	0.00

Summation of wave force = 1.66kN

Summation of moment generated from wave force = 14.75kN.m

Moment arm = 24.2/2.73 = 8.86 meter

Load generated from Floating Debris

Load from floating debris = $F_h = 0.5 * \frac{\gamma_w}{g} * e * h_d * u_s^2$

Here,

$\gamma_w = density\ of\ water = 10\ kN/m^3$

g= gravity = 9.8 m/sec^2

h_d= Depth of floating debris = 1 meter

e = permeability = 0.67

Floating debris load = 0.83 kN

Moment arm of the floating debris = 8.4 meter

Calculation of embedment length

Summation of force on a wooden pile,

$$F_{res} = \sum_{z=0}^{z=h} F_h(current) + F_h(wave) + F_h(floating\ debris) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

From equation 7,

F_{res} = (1.65+2.73+0.83) kN = 5.20 kN

Summation of moment on a wooden pile

$$M_{res} = \sum_{z=0}^{z=h} F_h(current).z_{sc} + F_h(wave).z_{sw} + F_h(floating\ debris).z_{sfd} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

M_{res} = 1.65*7.4 + 2.73*8.86 + 0.83*8.4 = 40.5 kN.m

The lever arm h_{res} of the resulting force is defined by,

$$h_{res} = \frac{M_{res}}{F_{res}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

From equation (9), h_{res}= 40.5/5.20 = 7.8 meter

From equation (8)

$$\sum M = 0 \rightarrow F_{res}(h_{res} + t_0) - f_w \frac{Dt_0^2}{2}.\frac{t_0}{3} - f_w.\frac{t_0^3}{6}.\frac{t_0}{4} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$t_0^4 + 4Dt_0^3 - \frac{24}{f_w}.F_{res}.t_0 - \frac{24}{f_w}.F_{res}.h_{res} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$f_w = \gamma \; tan^2(45 + \frac{\emptyset}{2})$……………………..(12)

Here,

γ = density of subsoil = 1442.2 kg/m^3

from equation 12, f_w = 4327 kg/m^3 = 4.80 t/m^3

Solving the equation 11,

$$t_0^4 + 4 * 0.2 * t_0^3 - \frac{24}{4.80} * 4.14 * t_0 - \frac{24}{4.80} * 4.14 * 7.50 = 0$$

Solving the above equation,

t_0 = 3.90 meter

t_{design} = 1.25*3.90≥5.0

=4.85 ≥ 5.0

<u>**Strength check for wooden pile**</u>

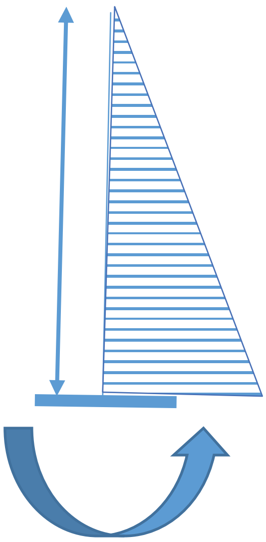

Figure 6-13:Bending moment diagram

Bending stress, $\sigma = \frac{Mc}{I}$

Inertia of wooden pile, $I = \frac{\pi r^4}{2}$

Radius of pile = 0.1 meter

Hence moment of inertia of the system = 3.1416*(0.1)^4/12

= 0.000157 m^4

Bending stress = 21.5*0.1/ (0.000157) kN/m^2 = 13694 kN/m^2 = 13.7 MPa

Modulus of rapture= *shorea robusta* (sal) = 850 kg/cm^2

= 83 MPa

The calculation of pile length and number are as follows:

Table 6-6: Protrusion length and total pier number in Baroaria

Chainage	Spur Name	Protrusion Length (meter)	Total Pier no. in one layer	Pier no. according to standard pier length		
				5m	10m	14m
Chainage 0+000	Confluence of river					
Chainage 0+125	Spur -01	30	63	11	16	36
Chainage 0+225	Spur -02	50	99	28	47	24
Chainage 0+350	Spur -03	50	100		26	74
Chainage 0+475	Spur -04	50	97		36	61
Chainage 0+600	Spur-05	50	99	13	71	15
Chainage 0+725	Spur-06	50	99	13	71	15
Chainage 0+850	Spur-07	25	49		49	
Chainage 0+975	Spur-08	25	50		20	30
Chainage 0+1115	Spur-09	50	102	11	40	51
Chainage 0+1215	Spur-10	30	61		38	23
Chainage 0+1285	Spur-11	20	39		39	
Chainage 0+1355	Spur-12	20	39		39	
Chainage 0+1425	Spur-13	20	39		39	
Chainage 0+1495	Spur -14	20	39		39	

Table 6-7:Protrusion length and total pier number in Chadgar

Chainage	Spur Name	Protrusion Length (meter)	Total Pier no. in one layer	Pier no. according to standard pier length		
				5m	10m	14m
Chainage 4+000	Spur -015	25	48			48
chainage + 4065	Spur -016	25	48			48
chainage + 4130	Spur -017	25	51	18	33	
chainage + 4195	Spur -018	25	51	18	33	
chainage + 4260	Spur -019	25	49		49	
chainage + 4325	Spur -020	25	49		49	
chainage + 4410	Spur -021	35	71		52	19
chainage + 4495	Spur -022	35	70	40	18	12
chainage + 4580	Spur -023	35	70		70	
chainage + 4665	Spur -024	35	70		70	
chainage + 4750	Spur -025	35	68		68	
chainage + 4875	Spur -026	50	98		55	43
chainage + 5000	Spur -027	50	97	20	77	
chainage + 5100	Spur -028	40	78	20	58	
chainage + 5200	Spur -029	40	83	11	35	37
chainage + 5300	Spur -030	40	83	11	35	37
chainage + 5400	Spur -031	40	80	48	32	
chainage + 5500	Spur -032	40	80	48	32	

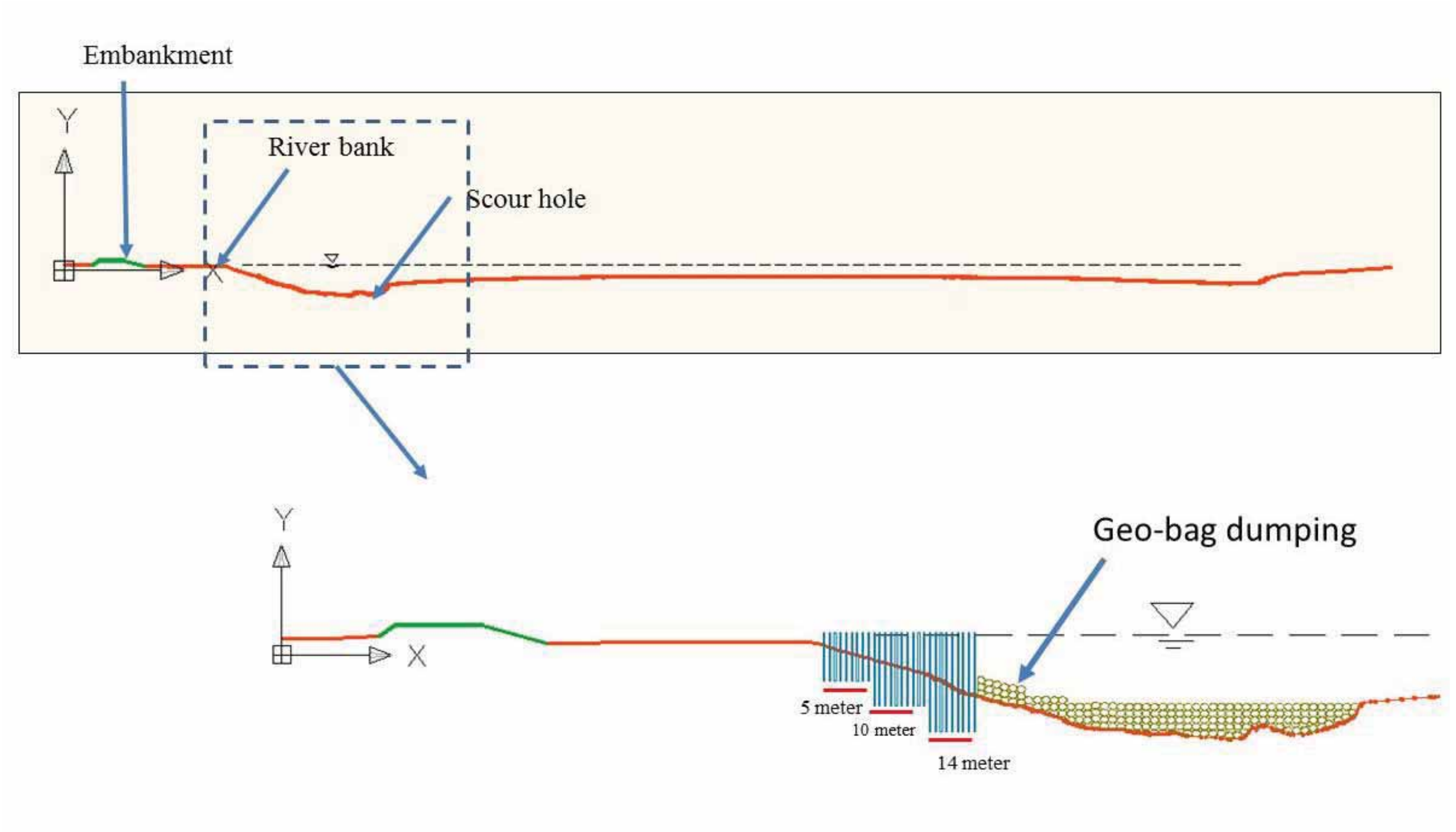

Figure 6-14: Semi-permeable spur upto scour hole + Geo-bag dumping at scour hole(Option-1)

OPTION-2: SLOPE PROTECTION WITH CC BLOCK + GEOBAG DUMPING

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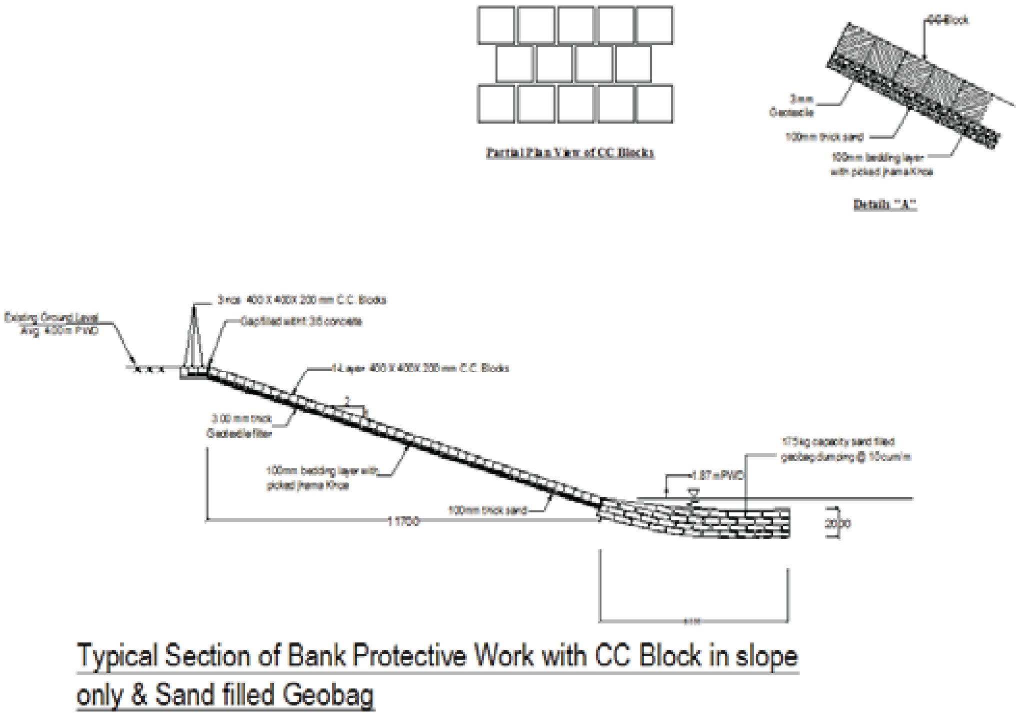

Figure 6-15: Geobag with CC block (Option-2)

OPTION-3: SEMI-PERMEABLE TIMBER SPUR

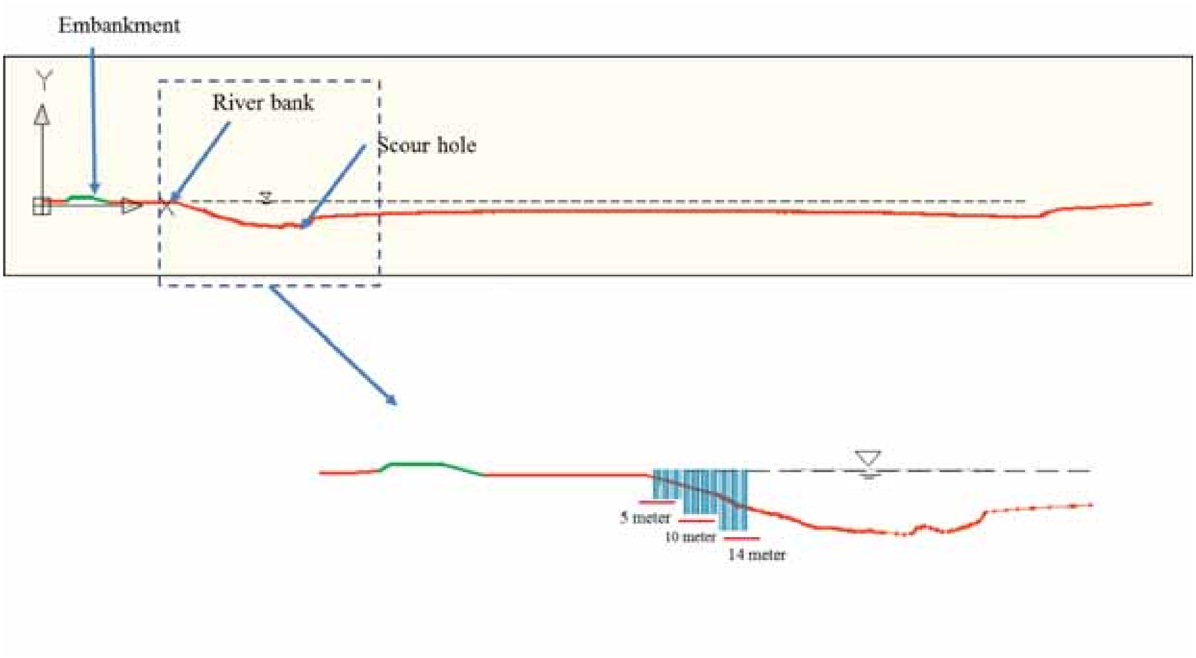

Figure 6-16: Semi-permeable spur upto scour hole

6.8.3 Costing

The purpose of cost estimate is to prepare investment cost of the project for different options. The estimated cost has also been used for selection of the most appropriate option.

The cost estimate of proposed protection works is prepared on the basis of estimated quantity from prepared drawings and rates are taken from current "Standard Schedule of Rates Manual, Volume II; Item and Element Rates" of Feni O & M Circle, BWDB, Feni effective for the year 2014-2015.

The total estimated cost for option-1 is Tk 49.00 million, for option -2 Tk 243 million and for option-3 it is Tk 23.00 million. The cost of each option is given in Table 6-8.

Table 6-8: Costing of different options

Option	Cost of Protection system (BDT)	Total Cost (BDT)
Semi-permeable timber spur + Geo-bag dumping at the scour hole	Semi permeable Spur = 20.16 million	49.00 million
	1meter top block using Drum sheet=0.34 million	
	Brick-bats at the bottom of semi-permeable spur =2.50 million	
	Geobag dumping cost= 25.80 million	
Slope protection with CC block + Geobag dumping	Slope protection with CC block = 217.30 million	243 million
	Geo-bag= 25.90 million	
Semi-permeable timber spur	Semi-permeable spur installation cost = 20.16 million	23.00 million
	1meter top block using Drum sheet = 0.34 million	
	Brick-bats at the bottom of semi-permeable spur = 2.50 million	

6.8.4 Structural Stability

Structure and Overall Stability

The starting point for most timber groyne structures is the use of single cantilever piles. Depending on the operating conditions it is sometimes necessary to modify or supplement this approach with other techniques such as planting the posts in concrete or the use of ties or props. On the other hand, a structural system can provide structural stability to the system of groyne.

The stability of a groyne structure is determined by its ability to withstand loads exerting a moment on the structure. Usually evenly spaced cantilevered main piles with buried in-fill panels of vertical sheet piles or horizontal planks achieve overall stability. The stability of a groyne can be affected by scour and undermining of the foundations. The means of attaining sufficient stability dependent on the bank type in which the groyne is to be founded.

Members and Connections

All fixings are exposed to severe wear and oxidation. Therefore as few bolts or coach screws, as possible should be used, these never being placed in the same grain line of the timber. Galvanised steel fixings are commonly used but stainless steel fixings have the advantage that the groyne can be dismantled or refurbished more easily and the fixings can be reused.

Finishes and Fittings

When driving timber piles, the end fibers have the tendency to separate (broom) at both the head and toe of the pile, resulting in a loss of structural strength. Pile rings and shoes can be fitted to protect the head and toe of the piles.

Natural Environment

To protect piles from abrasion, softwood or recycled timber rubbing pieces can be attached to the piles at critical levels. Extending planks beyond piles may also reduce wear, increasing the life of the pile. Members should be sized with an allowance for wear and the connections carefully chosen. On some sand beaches ply panels have been fixed to the groynes preventing sand being transported between the planks, thus minimising abrasion, which increases dramatically with the size of the gap. Reuse and recycling of timber can substantially reduce the need for new timber, and should be incorporated in the design and maintenance of structures.

6.9 Final selection of Mitigation Measures for Bank Protection Work

Option -1 has been selected the best suitable option for mitigation measures. Based on the model result analysis, series of permeable spurs making an angle 60^0 to the bankline is the most suitable for bank protection measure. Impermeable spurs provide good main channel formation potential, on the other hand permeable spur induces reduced bank parallel spur field velocity, offering good bank building prospect. Though the average spur field velocity is less in impermeable case, the return current causes bank and spur field erosion. The scour depth around the impermeable structures is huge compared to the moderate scour around permeable spurs.

A good river course should have efficient conveyance capacity along with navigability, less bank erosion and environmentally compatible to the local need. Considering all these criteria, to solve the problems of different kinds of structures, a combination of permeable spur and traditional bandal is designed and examined experimentally (Khaleduzzaman, 2004). The structure is named as ‘Top Blocked Permeable Spur’ since for the structural safety and spur field velocity reduction eventually the permeable spur piles will play major role. The basic difference of top blocked semi-permeable spur and impermeable spur is the free passage through the bottom opening and flow reduction by the piles. As a result the recirculation flow will be reduced or diminished and effective flow diversion towards the main channel will be obtained. With permeable spur it differs in terms of blockage at the top, thus ensuring more flow diversion in the main channel. As a consequence, deeper main channel can be obtained.

It can be concluded that top blocked semi-permeable spurs will provide deeper navigation channel and protected bank with deposition. It will also play an important role for stabilization and restoration of rivers. Top blocked semi-permeable spur (1.5 m from top of the spur should be blocked by GI sheet) making an angle 60^0 with bank line is recommended for bank protection measures (option -1). Protrusion length of the spur is upto scour hole. Sand-filled geo-bag will be dumped in the scour hole. The spacing of the spur along the bank is 2.5L (where L = protrusion length). In order to avoid or minimize scouring around the bottom of the wooden pile, dumping of brick bats are suggested. A pair of horizontal wooden piles are recommended to tie all vertical members of a permeable spur along the whole length. One wooden pile should be 3 meter below from top of the permeable spur and another pile should be 3 m above from the bed level.

The cost of this mitigation measure also very less compare to traditional bank protection measures.

6.10 Terminal Groyne at Two Ends of Mitigation Measures

If transfer of material is at any point interrupted, either naturally or by a protective structure such as a groyne or seawall, then the local sediment budget is adversely affected. Material tends to be washed out to river leaving adjacent bank and allowing current to deliver greater destructive energy at the two end of defensive work. Shortly after a defensive structure is put in place, immediately two end of the work begins to erode at an increased rate, often dramatically. The resulting indentation develops a characteristic crenulate shape (from the Latin word for notch), which eventually extends some distance along the bank. Part of the embayment process attempts to creep behind or outflank the defence. In time, the rate of loss will stabilize as the system adjusts to a position of equilibrium, or pattern of erosion similar to the normal erosion in general, though the distinctive crenulate indentation remains.

To minimize the effects, two terminal Groynes at the two ends of the protective works at each location is suggested.

6.11 Specification of Construction Materials

Specification of Timber Pile

Dia of pile: Minimum 8 inch (Butt) & 6 inch (Tip)
Length of pile: Minimum 4 m (Pile lengths should be measured and recorded along with butt and toe diameters.)
Preservatives: Coal Tar or creosote-based preservatives.
Special requirement: trim all limbs and knots flush with the surface
Straightness: Piles shall also be free from short crooks that deviate by more than 2.5 inches from straightness in any 5 feet length.

Specification of Geo bag Pile

Geo-bag; size: 1200 mmx950 mm;

Geo-fabric thickness: 3.0 mm;

Fill Volume: 0.1664 cubic meter;

Weight: 250 kg

Unit cost: 451 Tk/bag

Geotextile used as Sub-layer for the Launching Apron

For the use of geotextile underneath a launching apron (articulating mattress) the material must be able to resist larger tensile stresses. The fabric (non-woven needle punched) should have the following specification:

Material: Preferably 100% polyester (PES) / 50% polypropylene (PP) and 50% PES
· Characteristic opening size O90 ≤ 0.08 mm
· Thickness (under 2 kPa pressure) ≥ 3.00 mm
· Mass per unit area ≥ 500 gm/m^2
· Wide width tensile strength ≥ 25 kN/m
· Grab strength ≥ 1600 N
· CBR puncture resistance ≥ 4500 N
· Elongation (both direction) ≥ 40% and ≤ 90%
· Permeability (both direction, under 2 kPa pressure) ≥ 2x10-3 m/s

Sand:

FM>0.90 and minimum 90% sand must be retained on sieve no 100,

Sewing/spacing of sew:

Sewing should be done with at least two thread type by machine with lock stitch (Type 301 under ISO 4915/DIN 61400) or double chain stitch (Type 401 under ISO4915/DIN 61400). All sewing is subject to acceptance of the Engineer-in-charge after testing of samples. Number of stitch per inch should be 6nos. Minimum margin from the edge of geotextile to the stitch line should be 20mm.

Thread :

Thread for stitching should be 100% polypropylene or nylon.

Specification of GI Sheet

Thickness: Minimum 1.2 mm
Width: 300 ~ 500 mm
Grade: 270 N/mm^2 (MPa)
Coating: Proper coating provided for anti-corrosion.

Specification of Brick Bats

The brick bats is recommended around the bottom of the wooden pile which is shown in Figure 6-17

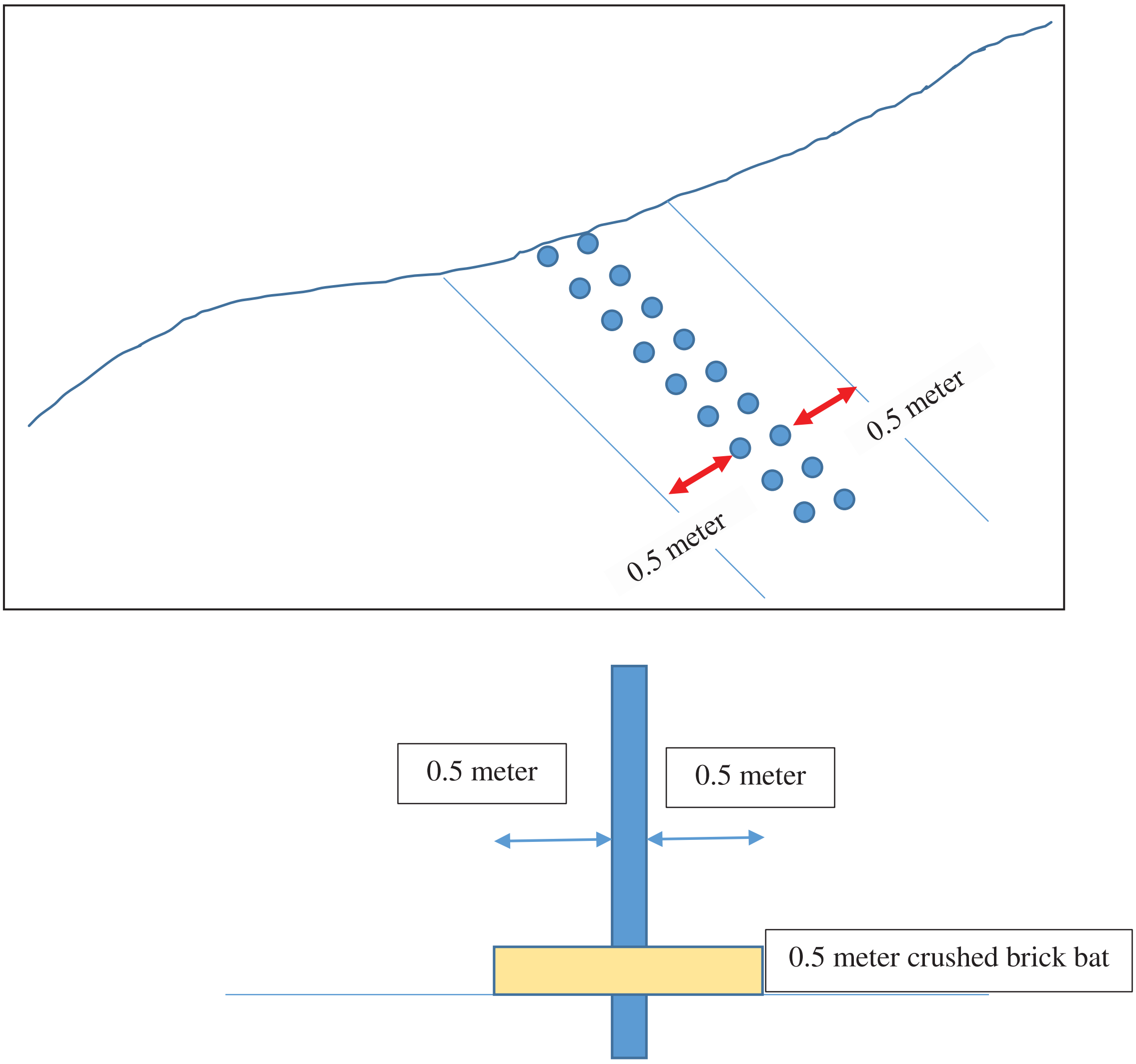

Figure 6-17 : Brick bats around the bottom of the wooden pile

The specifications of brick bats are given below:

Unit weight: 120 pcf
Size: Half of a standard brick size (Std. brick size: 9.25”x4.5”x2.75”)
Compressive strength: 20 ~ 27.6 MPa

6.12 Implementation of Mitigation Measures as Pilot Basis

It is decided in the meeting held on 29th February at Blue Gold office to observe the effectiveness of the proposed mitigation measures as a pilot basis before implementation for whole erosion vulnerable area. Primarily six permeable spurs have been considered along the bankline which cover approximately 500 m erosion vulnerable river bankline. The location of proposed erosion mitigation measures as pilot basis is shown in Figure 6-18. The total cost for implementation of these protective measures is about BDT 49 million.

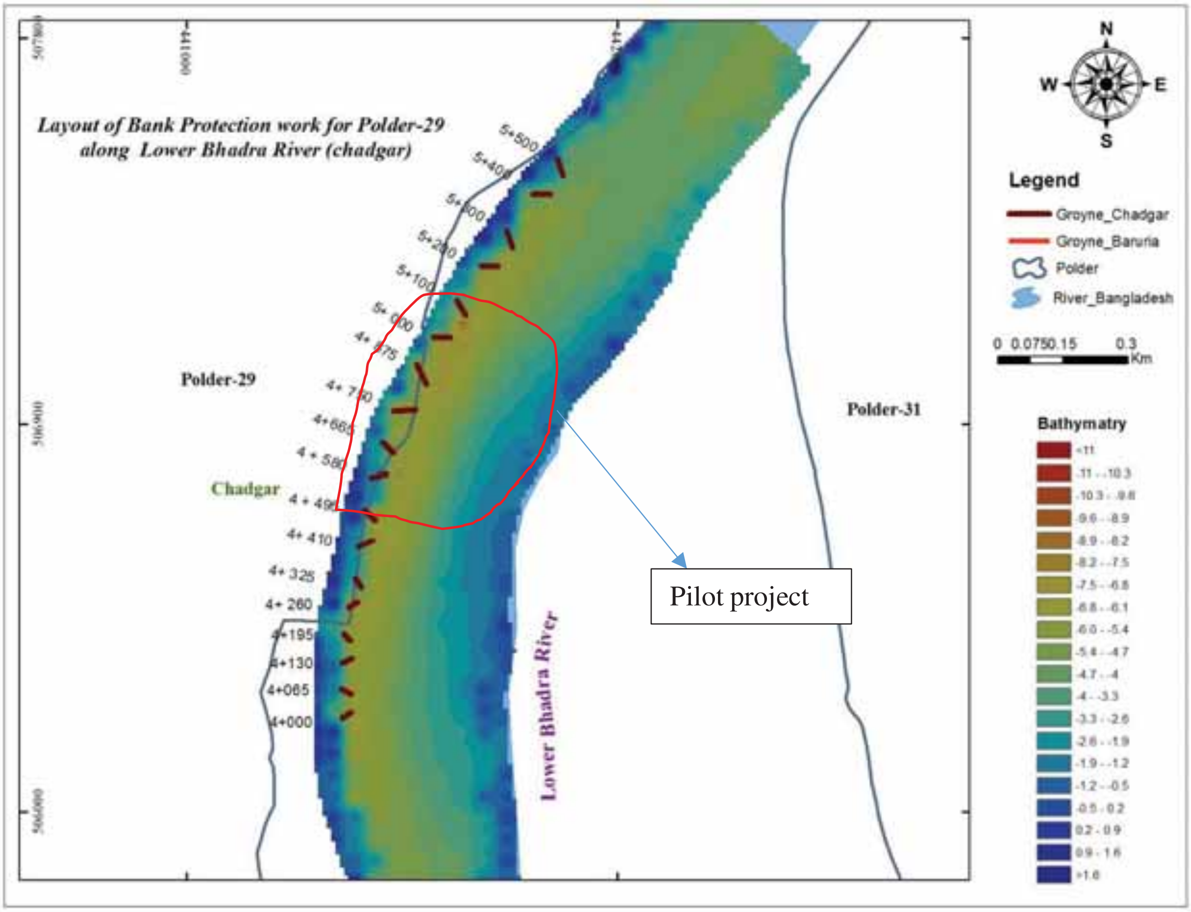

Figure 6-18: The location of proposed erosion mitigation measures as pilot basis

Total cost for pilot project

Total cost for implementation of the mitigation measure as pilot basis along 500 m river bank is BDT 7 million. Details of costing for pilot project is given in Appendix-A

Option	Cost of Protection system (BDT)	Total Cost (BDT)
Semi-permeable timber spur + Geo-bag dumping at the scour hole	Semi permeable Spur = 4.20 million	7.00 million
	1meter top block using Drum sheet=0.082 million	
	Brick-bats at the bottom of semi-permeable spur =0.50 million	
	Geobag dumping cost= 2.20 million	

6.13 Driving of Wooden Bullah Piles to Protect Bank Erosion

At present, a stretch of about 520 m from km 4.580 to 5.100 of most critical zone out of total 3008 m existing erosion length will be addressed first. Total 6 number of permeable spurs with three different lengths of wooden bullah piles (5 m, 10 m & 14 m) required as per existing slope condition will be driven in two rows 2.0 feet (0.60 m) apart from each other. The length of a spur with perpendicular to the bank or flow varies from 35 m to 50 m consist of 68 to 98 number of Bullah piles respectively depending on the existing slope condition. The bullah piles to be driven @ 16” clear space in each row. The number and each length of piles are given in Table 6-6 and Table 6-7.

All piles will be either painted or soaked with bitumen and be naturally dried duly before driving. Driving end of a pile will be sharp-pointed as far as possible so that the resistance force during driving of piles become minimum. To guide the drop of *‘Monkey Weight’* through a ¾” diameter guide rod, there will be an (+) ¾” Φ augur hole of length 2.0 to 2.5 times of pile’s diameter at the center-top of each pile. The ‘drop height’ should be carefully selected so that buckling of pile cannot occur due to impact particularly to the piles of greater length. During driving, all piles should remain truly vertical with the help of guys if necessary. To have a 14m long pile, two piles of each 7.0 m length should be joined together as per suggestion detail shown in Figure 6-19 and Figure 6-20 .Chainage poles should be firmly fixed at the 0.0 bank line tied one end of a long nylon rope at the pole and other end reach at the opposite bank crossing the river. Nylon rope should be tied with colored-flags to mark the spacing of the piles perpendicular to the bank line for exact positioning of the individual wooden bullah piles.

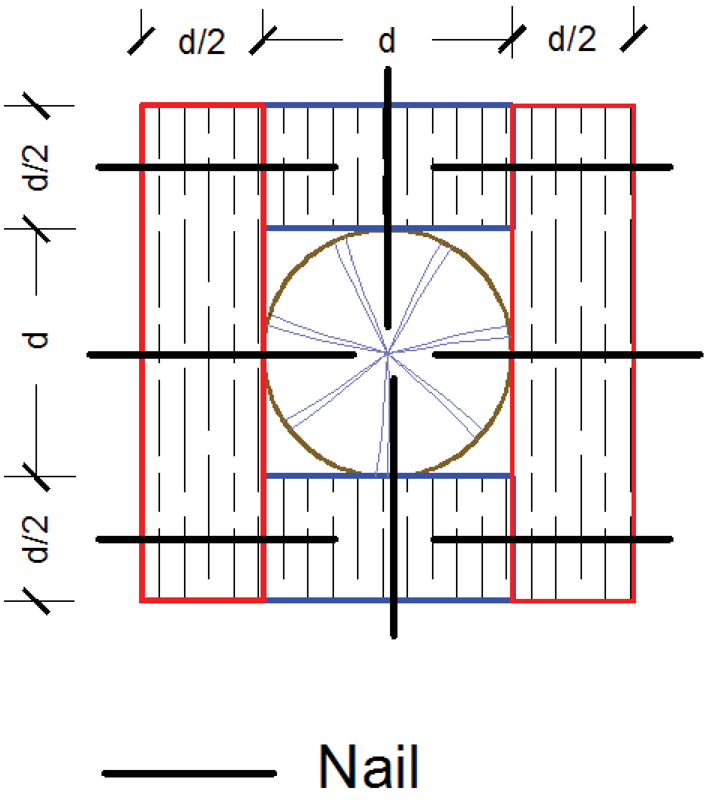

Figure 6-19 : Cross-section View of the joint

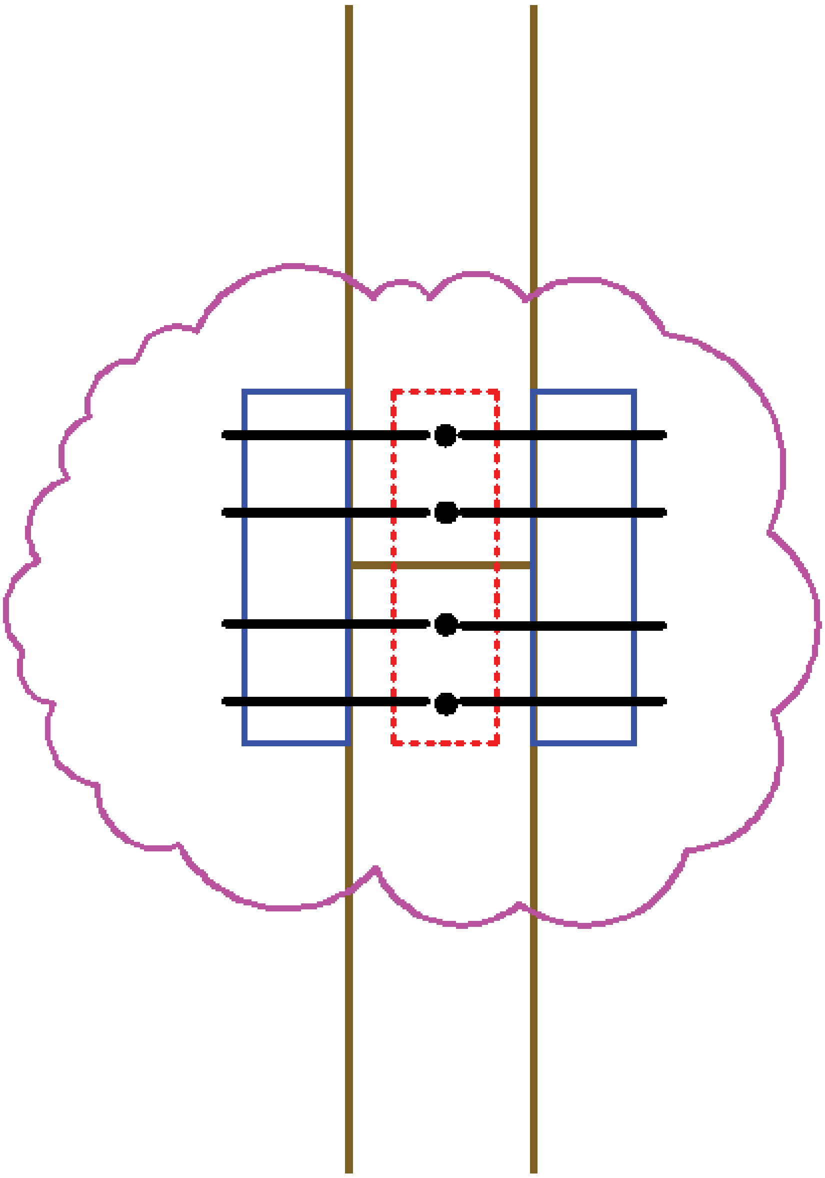

Figure 6-20: Side view of the joint

It is suggested to start driving of bullah piles from the bed side of the river and to proceed towards the eroded bank (0.0 line) which distances have been shown in Table 6-6 and Table 6-7. Piles to be driven below the water level should be done with the help of a pair of boats tied together having a workable gap between the two boats. During driving, top of each pile must remain above the water level.

6.14 Construction and Monitoring

It is not reasonably possible to develop structures that are maintenance free. In terms of maintenance and operation it will need some special care or manual to maintain the blockage ratio. Maximum blockage should not exceed 50%. One of the reasons for providing maximum blockage of 50% may be that, it will be difficult to make the structure (made by the local materials like wooden log or bamboo etc.) safe against the impact of monsoon flow with more blockage. Blockage can be made by Galvanized Iron (GI) Sheet. Local erosion around the structures it needs periodic monitoring and maintenance. As local scour around the structure is much less than impermeable spur, maintenance of semi-permeable spurs is the least compared to other structures.

The proposed bank protective works need to be monitored and subsequently maintenance of the same shall be undertaken on regular basis. Effectiveness of bank protection measure largely depends on proper monitoring .Monitoring is a process that provides information and ensures the use of such information to assess the project effects. It helps to enhance the performance and achieve desired results of any bank protection measures by improving the current and future plan for maintenance and other things. The data and information generated by the monitoring system is a way of analyzing present performance and future work plan.

The monitoring consists of following activities:

1. Identification of abnormal scour hole at different parts of permeable spur including upstream and downstream terminations through hydrographic survey before and after monsoon.
2. Assessment of sedimentation along the protective area and bank erosion or not
3. Assessment of bank line shifting at upstream and downstream of permeable spur by land survey once in a year.
4. Visual inspection of works that are above low water levels.
5. Measurement of current speed during monsoon.

In view of above, it is recommended to adopt following measures considering monitoring and maintenance activities:

- Routine visual inspection of permeable gryone/spur;
- Keeping the blockage at least 40%;
- Survey of sections at suitable interval before, during and after monsoon;
- Survey of bank line shifting at upstream and downstream of spur;
- Keeping annual maintenance cost including and
- Immediate repair of any damage of spur to avoid major rehabilitation.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Polder 29 has been experiencing bank erosion problem for long time and the embankment was retired several times due to severe erosion of the Lower Bhadra river. Homestead and productive land is eroding. Local community has strong demand for protection of their land by erosion mitigation measures. For development of a comprehensive, ecologically sustainable and innovative erosion protection measure, data of the study area has been collected and an updated model of this river system has been developed. Model has been developed by using MIKE21FM modelling system covering the river network system of the study area using recent hydro-morphological data to identify the erosion prone areas and to undertake probable mitigation measures. Hydraulic characteristics, current speed, the flow distribution in the different rivers of the adjacent areas have been analyzed for dry and monsoon seasons using simulation results.

The analysis of satellite imageries, bathymetric surveys and model simulation results show that the area is morphologically highly dynamic, changing its planform continuously. The valuable land of this upazila is rapidly losing as the Lower Bhadra River is incessantly eroding its banks. Satellite image analysis shows that from 2011 to 2015 about 18.10 ha land has been eroded away along the right bank of Lower Bhadra River. Based on near bank velocity, flow distribution, bank slope, position of thalweg line, previous erosion-deposition history and future trend of erosion, critical location of bank erosion has been identified. Near Chadgar the vulnerable length under erosion threat is about 1.63 km and near Baroaria it is about 1.45 km. Total 3.08 km length at the right bank of Lower Bhadra river needs bank protection measure at two locations.

Series of top blocked (1.5 m from the top of the spur) semi-permeable spurs with sand filled geo-bag in the scour hole (option-1) has been recommended as erosion mitigation measure. Top blocked semi-permeable spur has been considered along 1.63 km length near Chadgar and 1.45 km near Baroaria (Figure 5-10) along the right bank of Lower Bhadra river.

Maximum protrusion length is limited to 50 meter. The protrusion length of each spur varies from 25 – 50 m at Chadgar and 20 – 50 m at Baroaria. Protrusion length of the semi-permeable spur is determined by distance between river bank to the local scour hole. The reason to limit the protrusion length of spur up to the scour hole is to minimise the length of wooden piles of the spurs. The spacing of permeable spur along the river is 2.5L, where L is the protrusion length of the permeable spur. Spacing varies based on the protrusion length of the permeable spur. Maximum spacing between two permeable spur is 125 m. Spacing of the semi-permeable spur varies from 65-125 m in Chadgar and 70-140 m in Baroaria. The scour hole will be filled by sand filled geo-bag. The semi-permeable spur is designed by full blockage of 1.5 m from top. The remaining part of the spur has 40-50% blockage and 60-50% open. Top blockage can be made with Galvanized Iron (GI) Sheet. The semi-permeable spur would be constructed by wooden pile. The diameter of each wooden pile is 0.2 m. Sand filled geobag will be dumped in the scour hole and the semi-permeable timber spur will be provided up to the starting of scour hole. Brick bats are suggested for dumping to avoid or minimize the scouring around the bottom of the wooden piles. It is recommended to tie the whole length of the permeable spur by a pair of horizontal wooden piles vertical to the bank line. One wooden pile is to be located at 3 m below from top of the permeable spur and another pile at 3 m above from the bed level. Each of the two horizontal "tie piles" should be fixed firmly with the vertical member of a spur with G.I nut-bolts /screws through a hole drilled at the crossing of the horizontal and the vertical wooden piles of a spur) to act as a monolithic member.

Simulation result with permeable spur without top blockage shows that there is reduction of current speed from 30% to 40% due to the permeable spur which shifts the attacking direction of velocity and flow from riverbank towards the river bed. This spur will also trap the sediment and deposit it near the bank.

Model does not provide local scour information around wooden pile in the semi permeable spur system. Local scour has been calculated considering the simulated velocity and the empirical equations.

Monitoring and maintenance of bank protection work is highly essential. Routine visual inspection of permeable spur, survey of section at suitable interval before, during and after monsoon, monitoring of bank-line shifting and keeping sufficient wooden piles will be necessary to undertake maintenance works.

7.2 Recommendations

I. It is recommended to protect the total 3.08 km erosion vulnerable river bank along the right bank of Lower Bhadra river by series of semi-permeable spur with sand filled Geobag dumping (option-1). The top of semi-permeable spur will be blocked by Galvanized Iron (GI) sheet. The semi-permeable spur is designed by full blockage of 1.5 m from top. The remaining part of the spur has 40-50% blockage and 60-50% open. The protrusion length of the spur is upto scour hole. Maximum protrusion length is around 50 m. The spacing of the spur along the bank is 2.5L (L= Protrusion length). In order to avoid or minimize scouring around the bottom of the wooden pile, dumping of brick bats are suggested. A pair of horizontal wooden piles are recommended to tie all vertical members of a permeable spur along the whole length. One wooden pile should be 3 meter below from top of the permeable spur and another pile should be 3 m above from the bed level.

II. The proposed bank protective works need to be monitored to generate data, information, and new knowledge and to take corrective measures in time. The monitoring consists of following activities:
   - Routine visual inspection of permeable spur;
   - Survey of sections at suitable interval before, during and after monsoon;
   - Survey of bank line shifting at upstream and downstream of spur;
   - Keeping annual maintenance cost including and
   - Immediate repair of any damage of spur to avoid major rehabilitation.

III. Before Implementation of the erosion mitigation measures as whole, it is recommended to implement on a pilot basis for monitoring the effectiveness this work and to review and make necessary correction/modification if necessary in the design /implementation process.

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Appendix A: Cost Estimate

Costing and Details of Joint

Option -01

(Semi-permeable timber spur **+ Geo**-bag dumping at the scour hole)

Total cost of semi-permeable spur installation at the site = 20.16 million BDT

Total cost of providing 1meter top block using Drum sheet = 0.34 million BDT

Total cost for providing brick-bats at the bottom of semi-permeable spur = 2.50 million BDT

Total cost for geobag dumping at the scour hole = 25.80 million BDT

Total cost of protection system = 49 million BDT

Option -2

Option-3

(Semi-permeable timber spur **+ Geo**-bag dumping at the scour hole)

Total cost of semi-permeable spur installation at the site = 20.16 million BDT

Total cost of providing 1meter top block using Drum sheet = 0.34 million BDT

Total cost for providing brick-bats at the bottom of semi-permeable spur = 2.50 million BDT

Total cost of protection system= 23 million BDT

Cost of geo bag filling at Baroaria

Chainage	Filling Area (sq.meter)	level of filling	Filling Volume (cubic meter)
chainage 0+000	44	-5 mPWD	
chainage 0+100	12	-6 mPWD	2800
chainage 0+200	4	-6 mPWD	800
chainage 0+300	30	-5 mPWD	1700
chainage 0+400			
chainage 0+500			0
chainage 0+600	30	-5 mPWD	1500
chainage 0+700	55	-5 mPWD	4250
chainage 0+800	12	-6 mPWD	3350
chainage 0+900	52	-8 mPWD	3200
chainage 01+000	105	-7 mPWD	7850
chainage 01+100	230	-6 mPWD	16750
chainage 01+200	9	-6 mPWD	11950
chainage 01+300	9	-6 mPWD	900

Total volume = 55050 cubic meter

Vol. of single bag = 0.1667 cubic meter

No. of Bag = 330234

Unit cost for dumping bag = 64 (@ Noakhali)

Total cost = 21.14 million BDT

Cost of geo bag filling at chadgar

Chainage	Filling Area (sq.meter)	level of filling	Filling Volume (cubic meter)
chainage 4+100	11	-6 mPWD	1350
chainage 4+200	10	-6 mPWD	1050
chainage 4+300	8	-6 mPWD	900
chainage 4+400	9	-6 mPWD	850
chainage 4+500	9	-6 mPWD	900
chainage 4+600	10	-6 mPWD	950
chainage 4+700	5	-6 mPWD	750
chainage 4+800	11	-6 mPWD	800
chainage 4+900	6	-6 mPWD	850
chainage 5+000	8	-6 mPWD	700
chainage 5+100	9	-6 mPWD	850
chainage 5+200	8	-6 mPWD	850
chainage 5+300	5	-6 mPWD	650
chainage 5+400	8	-5 mPWD	650

Total =12100 cubic meter

Vol. of single bag = 0.1667 cubic meter

No. of Bag = 72585

Unit cost for dumping bag = 64 (@ Noakhali)

Total cost = 4.65 million BDT

Cost of Brick-Bat for Scour protection at the bottom of semi permeable spur

Location: Baroaria	Protrusion Length of spur (meter)	volume of brick bats (m^3)
Chainage 0+000		
Chainage 0+125	30	15
Chainage 0+225	50	25
Chainage 0+350	50	25
Chainage 0+475	50	25
Chainage 0+600	50	25
Chainage 0+725	50	25
Chainage 0+850	22	11
Chainage 0+975	18	9
Chainage 01+115	50	25
Chainage 01+215	30	15
Chainage 01+285	20	10
Chainage 01+355	20	10
Chainage 01+425	20	10
Chainage 01+495	20	10
Volume of brick		240
Number of Brick		118021
Cost in BDT (million)		1.10

Cost of Brick-Bat for Scour protection at the bottom of semi permeable spur

Location: Chadgar	Protrusion Length (meter)	volume of brick bats (m^3)
Chainage 4+000	25	12.5
chainage + 4065	25	12.5
chainage + 4130	25	12.5
chainage + 4195	25	12.5
chainage + 4260	25	12.5
chainage + 4325	25	12.5
chainage + 4410	35	17.5
chainage + 4495	35	17.5
chainage + 4580	35	17.5
chainage + 4665	35	17.5
chainage + 4750	35	17.5
chainage + 4875	50	25
chainage + 5000	50	25
chainage + 5100	40	20
chainage + 5200	40	20
chainage + 5300	40	20
chainage + 5400	40	20
chainage + 5500	40	20
Volume of brick		312.5 m^3
Number of Brick		153673
Cost in BDT (million)		1.40

Cost of Top block for semi permeable spur

Location: Baroaria	Protrusion Length (meter)	Area of Drum sheet (sq. m)
Chainage 0+000		
Chainage 0+125	30	30
Chainage 0+225	50	50
Chainage 0+350	50	50
Chainage 0+475	50	50
Chainage 0+600	50	50
Chainage 0+725	50	50
Chainage 0+850	22	22
Chainage 0+975	18	18
Chainage 01+115	50	50
Chainage 01+215	30	30
Chainage 01+285	20	20
Chainage 01+355	20	20
Chainage 01+425	20	20
Chainage 01+495	20	20
Area of drum sheet		480

Cost of drum sheet per square meter = 332.87 taka

Total cost of drum sheet required at Baroaria = 480 sq. m * 332.87 (taka/sq.m)

= 0.16 million BDT

Cost of Top block for semi permeable spur

Location: Chadgar	Protrusion Length (meter)	Area of Drum sheet (sq. m)
Chainage 4+000	25	25
chainage + 4065	25	25
chainage + 4130	25	25
chainage + 4195	25	25
chainage + 4260	25	25
chainage + 4325	25	25
chainage + 4410	35	35
chainage + 4495	35	35
chainage + 4580	35	35
chainage + 4665	35	35
chainage + 4750	35	35
chainage + 4875	50	50
chainage + 5000	50	50
chainage + 5100	40	40
chainage + 5200	40	40
chainage + 5300	40	40
chainage + 5400	40	40
chainage + 5500	40	40
Area of drum sheet		525

Cost of drum sheet per square meter = 332.87 taka

Total cost of drum sheet required at Baroaria = 525 sq. m * 332.87 (taka/sq.m)

= 0.175 million BDT

Cost calculation of semi permeable spur (Material cost, installation cost and labour cost)

Location: Baroaria	Groyne ID	Portrusion Length (meter)	Total Pier no. in one layer	Standard Length of pier		
				5m (Embedment 3.0 meter)	10m (Embedment 4.5 meter)	14m (Embedment 5.0 meter)
Chainage 0+000	Confluence of river					
Chainage 0+125	Groyne -01	30.0	63.0	11.0	16.0	36.0
Chainage 0+225	Groyne -02	50.0	99.0	28.0	47.0	24.0
Chainage 0+350	Groyne -03	50.0	100.0		26.0	74.0
Chainage 0+475	Groyne -04	50.0	97.0		36.0	61.0
Chainage 0+600	Groyne -05	50.0	99.0	13.0	71.0	15.0
Chainage 0+725	Groyne -06	50.0	99.0	13.0	71.0	15.0
Chainage 0+850	Groyne -07	25.0	49.0		49.0	
Chainage 0+975	Groyne -08	25.0	50.0		20.0	30.0
Chainage 1+115	Groyne -09	50.0	102.0	11.0	40.0	51.0
Chainage 1+215	Groyne -10	30.0	61.0		38.0	23.0
Chainage 1+285	Groyne -11	20.0	39.0		39.0	
Chainage 1+355	Groyne -12	20.0	39.0		39.0	
Chainage 1+425	Groyne -13	20.0	39.0		39.0	
Chainage 1+495	Groyne -14	20.0	39.0		39.0	

<u>Cost of wooden pier</u>

Supplying, sizing of local hard wood bullah = 7.40 million BDT

Labour charge for driving hard wood bullah = 1.54 million BDT

Assume lapping is required if length of single piece of bullah exceeds 5.0 meter,

Lapping cost calculated = 0.42 million BDT

Total cost = 9.36 million BDT

Cost calculation of semi permeable spur (Material cost, installation cost and labour cost)

Location: Chadgar		Protrusion Length (meter)	Total Pier No. in One Layer	Standard Length (number)		
				5m	10m	14m
Chainage 4+000	Groyne -015	25.0	48.0			48.0
Chainage 4+065	Groyne -016	25.0	48.0			48.0
Chainage 4+130	Groyne -017	25.0	51.0	18.0	33.0	
Chainage 4+ 195	Groyne -018	25.0	51.0	18.0	33.0	
Chainage 4+ 260	Groyne -019	25.0	49.0		49.0	
Chainage 4+ 325	Groyne -020	25.0	49.0		49.0	
Chainage 4+ 410	Groyne -021	35.0	71.0		52.0	19.0
Chainage 4 + 495	Groyne -022	35.0	70.0	40.0	18.0	12.0
Chainage 4 + 580	Groyne -023	35.0	70.0		70.0	
Chainage 4+665	Groyne -024	35.0	70.0		70.0	
Chainage 4+ 750	Groyne -025	35.0	68.0		68.0	
Chainage 4+ 875	Groyne -026	50.0	98.0		55.0	43.0
Chainage 5+ 000	Groyne -027	50.0	97.0	20.0	77.0	
Chainage 5+100	Groyne -028	40.0	78.0	20.0	58.0	
Chainage 5+ 200	Groyne -029	40.0	83.0	11.0	35.0	37.0
Chainage 5+ 300	Groyne -030	40.0	83.0	11.0	35.0	37.0
chainage 5+ 400	Groyne -031	40.0	80.0	48.0	32.0	
chainage 5+ 500	Groyne -032	40.0	80.0	48.0	32.0	

Cost of wooden pier

Supplying, sizing of local hard wood bullah = 8.50 million BDT

Labour charge for driving hard wood bullah = 1.86 million BDT

Assume lapping is required if length of single piece of bullah exceeds 5.0 meter,

Lapping cost calculated = 0.43 million BDT

Total cost = 10.80 million BDT

Cost of Pilot project

Application of the project area = 4+580 km to 5+100 km chainage

Geobag dumping

Chainage	Filling Area (sq.meter)	level of filling	Filling Volume (cubic meter)
chainage 4+500	9	-6 mPWD	900
chainage 4+600	10	-6 mPWD	950
chainage 4+700	5	-6 mPWD	750
chainage 4+800	11	-6 mPWD	800
chainage 4+900	6	-6 mPWD	850
chainage 5+000	8	-6 mPWD	700
chainage 5+100	9	-6 mPWD	850

Total =5800 cubic meter
Vol. of single bag = 0.1667 cubic meter
No. of Bag = 34793
Unit cost for dumping bag = 64 (@ Noakhali
Total cost = 2.2 million BDT

Brickbats at the spur bottom

Chadgar	Protrusion Length (meter)	volume of brick bats (m^3)
chainage 4+ 580	35	17.5
chainage 4+ 665	35	17.5
chainage 4+ 750	35	17.5
chainage 4+ 875	50	25
chainage 5+ 000	50	25
chainage 5+ 100	40	20
Volume of brick		122
Number of Brick		59994
Cost in BDT (million)		0.50

Application of Top block

Location: Chadgar	Protrusion Length (meter)	Area of Drum sheet (sq. m)
chainage 4+ 580	35	35
chainage 4+ 665	35	35
chainage 4+ 750	35	35
chainage 4+ 875	50	50
chainage 5+ 000	50	50
chainage 5+ 100	40	40
Area of drum sheet		245

Cost of drum sheet = 0.082 million BDT

Cost of wooden pier

Location: Chadgar		Length (meter)	Pier No.	Standard Length (number)		
				5m	10m	14m
Chainage 4 + 580	Groyne -023	35.0	70.0		70.0	
Chainage 4+665	Groyne -024	35.0	70.0		70.0	
Chainage 4+ 750	Groyne -025	35.0	68.0		68.0	
Chainage 4+ 875	Groyne -026	50.0	98.0		55.0	43.0
Chainage 5+ 000	Groyne -027	50.0	97.0	20.0	77.0	
Chainage 5+100	Groyne -028	40.0	78.0	20.0	58.0	

<u>Cost of wooden pier</u>

Supplying, sizing of local hard wood bullah = 3.30 million BDT

Labour charge for driving hard wood bullah = 0.70 million BDT

Assume lapping is required if length of single piece of bullah exceeds 5.0 meter,

Lapping cost calculated = 0.20 million BDT

Total cost = 4.20 million BDT

Total cost of the protection system = 7 million BDT

Appendix B: Comments and Responses

Comments and Responses on the Draft Final Report

Sl. No.	Comments	Responses
1	Section 1.4 includes the following products in a list of study outputs: detailed design of river bank protection works; validated model results, cost estimate of protective work; and recommendation of the monitoring and maintenance needs on the basis of response analysis. None of these products are presented in the report.(page-3)	All these are incorporated in the final report.
2	Section 5.2.2 states on page 34 that available satellite images of 2000, 2009 and 2015 were analyzed. However, Section 3.3.1 mentions on page 22 the purchase of satellite images of 2011 and 2015. Why was the 2011 image excluded from the analysis?(Page 4)	2011 image has been analysed and included in the final report.(page –xx)
3	Figure 5.4 shows banklines, but its caption suggests it shows a cross-sectional profile.	The caption has been corrected.
4.	Page 38 concludes from an image analysis that the river shifted towards East. This must be towards West. in this project area.	Agreed. It has been corrected in the Final Report.
5.	According to page 42, the locations of deep scour holes are among	The location of deep scour hole (thalweg line) has been shown

Sl. No.	Comments	Responses
	the criteria for selecting areas that are vulnerable to erosion. However, the report does not show any information on these locations.	in Figure 5.7
6	The first equation of Section 4.1 represents conservation of mass. Hence S is not an energy source-dissipation term but a source term for mass supply or withdrawal.	Equations were corrected
7	Flow velocities have overbars in the equations of Section 4.1, but these overbars are not explained. The overbar is missing in the second term of the second equation.	Equations were corrected
8	The minus sign at the end of the second equation suggests that the equation is not complete. The pressure, p , is not explained in the text. On the other hand, a, T are explained in the text but do not appear in the equations.	Equations were corrected
9	The fourth paragraph of Section 4.1 refers to Equations 13 and 14. However, the equations in the report do not have numbers.	It has been corrected.
10	The fourth paragraph of Section 4.1 refers to processes in the near-shore coastal zone. This is not appropriate for the present study on river bank erosion. Similarly, one would expect a bankline instead of a coastline in the first paragraph of Section 4.2.	Agreed. It has been corrected.
11	Section 4.3 has the title "Calibration and validation". However, the section presents only a calibration, no verification or validation.	Validation plot has been given in Figure in this final report.
12	According to Section 6.4, the model results lead to the conclusion that groynes making an angle of 40º to the bankline are the most	The permeable groyne has been represented in the model by series of pier. In MIKE21 hydrodynamic module, the effect of

Sl. No.	Comments	Responses
	suitable for bank protection. It is not clear, however, how these groynes have been represented on the computational grid of Figure 4.1. Deviations between groyne alignments and grid lines produce numerical artefacts that do not have any physical meaning.	bridge piers is modeled as sub-grid structures using a simple drag-law to capture the increasing resistance imposed by the piers as the flow speed increases. The effect on the flow due to the piers is modeled by calculating the current induced drag force on each individual pier. The horizontal coordinates in which the pier should be placed has to be specified. The angle of the pier, the streamline factor and the number of vertical pier sections has to be specified first. Then the geometry of the pier has been specified. Pier can be circular, rectangular or elliptical. Here circular pier has been used by mentioning the height and the width (diameter) of the pier. The number of pier is independent of grid. In one grid more than one pier can be specified. The hydrodynamic condition of the Lower Bhadra river has been simulated considering different orientation of the permeable groyne (series of pier) and assessed the best orientation to reduce the flow speed. And thus initially 40^0 angle has been selected for best option. It is further reviewed and finaly 60^0 with bankline has been selected as best suitable alignment for permeable groyne.
13	It would be useful to reflect on the information that can be derived from the numerical modelling. The modelling provides good insight in the present conditions, but it does not provide precise information on the near-bank flow conditions after implementation of the permeable groynes, because it does not take into account the	Agreed. It provides change in velocity and sediment depositions but not local scour. However, Local scour was calculated based on simulated velocity and using empirical formula.

Sl. No.	Comments	Responses
	morphological changes induced by the groynes. A morphological computation might be proposed, but that would not solve this as it would reproduce neither the local scour around the piles nor the resulting attraction of the thalweg towards the bank upstream and downstream of the protection (Mosselman & Sloff, 2002).	
14	The selection of measures has not considered the full range of possible options. Considerations of costs are missing too. Table 2.1 might be helpful in this respect.	A number of options were developed and estimated the cost for each option.
15	Figure 5.8 shows that no protection is planned along the bank at Jaliakhali. Extrapolation of the interpretation of bankline development in Figure 2.2 of the present document suggests, however, that substantial erosion may be expected there in the near future. This erosion might proceed even further up to the bank East of Baroaria.	Agreed. But river bank protection has been suggested at the most vulnerable locations which are presently experienced erosion problem and which have no setback distance.
16	The upstream and downstream terminations of river bank protections require special care, as they tend to become exposed by continued bank erosion. As a result, they are attacked from behind, upstream because the presence of the bank protection attracts the thalweg towards the bank, and downstream because flow separation may generate an eddy with returning flow. Moreover, in case of a continuous revetment, flow separation may increase turbulence and thereby produce additional local scour at the downstream termination. The report does not present any information on the design of these upstream and downstream terminations. The oblique groynes at the upstream and downstream ends of the bank protection	Upstream and downstream terminations have been considered.

Sl. No.	Comments	Responses
	structures in Figures 6.1 and 6.2 can be expected to increase the vulnerability of the terminations. They promote outflanking, which would enhance the bank erosion around the groynes at the terminations (Die Moran et al, 2013).	
17	Page 46 states that the permeable groynes can be constructed with wooden piles, without providing any considerations on the required length of the piles. The river near the bank at Chandgar is about 12 m deep. This depth will increase around the piles due to local scour. Additionally, the piles will have to penetrate sufficiently deep into the river bed for structural stability. Another point on page 46 is that the diameter of these long wooden piles is 1 m. This may pose serious challenges to pile driving.	It has been reviewed and the length of the all wooden piles has been calculated. Also penetration length (5 meter) has been determined considering all aspects. Now the maximum length of the wooden pile is 14 m. Pile diameter also reviwed and now it is suggested 8 inch (0.2 m) dia pile. These wooden piles have been arranged differently which is shown in Figure xx. All are incorporated in the final report.
18	More generally, the report does not provide information on the considerations behind the 50m groyne length, 50 m groyne spacing and 1 m diameter. No relation is given between the hydraulic loads and the details of the design. It is recommended to use the guidelines and design manual for standardized bank protection structures by Jamuna Test Works Consultants (2001b), albeit with caution because much of its contents has been derived from a single project without thorough testing for other cases. Apparently the guidelines and design manual have been updated later. Dr Knut Oberhagemann of Northwest Hydraulic Consultants might be the best informed person on this.	Agreed, In the latest study, Length of the groyne is reviewed; In a permeable groyne system, wooden pile is provided up to the location of river bend scour. Methodology for calculating Hydraulic load is incorporated in the final report.
19	Page 55 states that groynes making an angle of 40º to the bankline are the most suitable for bank protection. This does not comply with common practices in river training. Apparently this statement is based on the results	Groynes are arranged angularly to partially redirect the flow of water.

Sl. No.	Comments	Responses
	of hydrodynamic modelling that excludes 3D flow effects, morphological response and local scour. Moreover, Section 2.3 of the present document argues that the representation of these groynes on the computational grid of Figure 4.1 may have produced numerical artefacts without physical meaning.	Flow direction is possible by applying the top block sheet (1 meter)
20	Page 55 recommends the use of top-blocked permeable groynes as they will provide a deeper navigation channel. This will require special attention to the floating debris that will pile up against these blocked tops during floods, exerting additional loads on the structure.	Agreed; Load of floating debris has been considered in the calculation. Thickness of the floating debris is considered as 1 meter (as height of top blocked sheet is 1 meter in height).
21	(e.g. “ecosounder” must be “echo-sounder” on page 13). furthermore, some general guidance is given.	It has been corrected.
22	Romanization of Bengali names has not been applied consistently. Although there is noofficial standard for transcription, it is recommended to be consistent at least within the bounds of a single report. The present report by IWM (2015) uses the names “Baro-Aria” (p. 4), “Baraharia” (p. 6) and “Baroaria” (p. 13) for the same village. Similarly it uses “Chandgar” (pp. 4, 6) next to “Chadgar” (pp. 15, 30, 32) and “Cgadgar” (p. 30), “Salta” (p. 6) next to “Shalta” (pp. 7, 11), and “Gengrail” (p. 6) next to “Gangrail” (p. 7) and “Gangreil “ (pp.18, 19).	All have been corrected.
23	A space is compulsory between number and unit. For instance, “100m” and “250m” must be “100 m” and “250 m” on page 13;	All have been corrected.
24	The symbol for “hectare” is “ha”, not “Ha”, cf. pages 6, 36 and 38;	It has been corrected

Sl. No.	Comments	Responses
25	A valid unit of distance is km (kilometre), not Km (Kelvin metre), cf. page 15	It has been corrected
26	Exponents must be written as a superscript. Hence $2228m^3$/sec must be 2228 m^3/s on page 29	It has been corrected
27	The symbol for second is "s" instead of "sec". Hence $2228m^3$/sec must be 2228 m^3/s on page 29	It has been corrected
28	A double slash is not allowed. Hence "ha/km/yr" must be "ha/(km.yr)", "ha/(km yr)" or"$ha^1 km^{-1} yr^{-1}$", cf. pages 36 and 38	It has been corrected
29	Section 5.1.1 states that the dry-period tidal prism in the Lower Bhadra is about 50 Mm^3 = 50 cubic megametres = 50·10 $^{18}m^3$. This might be visualized as the volume of a 50,000 km high tower on a square surface of 1,000 × 1,000 km^2. This is incorrect. Correct ways of writing the intended volume are "50 million m^3" or "50 hm^3".	It has been corrected
30	The report contains various literature references, such as SWAIWRMP (2004), O'Brien (1931,1969), Lily (1989) and Khaleduzzaman (2004), but no list of references. This list needs to be added.	Agreed and will be incorporated
31	The term "bathymetric survey" on page 15 suggests that the measurements focused on water depths. Figure 5.3 shows, however, that river bed elevations have been measured with respect to Public Works Datum (PWD). This is indeed the correct input for the model. It is therefore recommended to use the term "bed topography survey" instead of "bathymetric survey", or to explain how bed topographies have been derived from bathymetries.	It will be explained in details. This is actually a river bed topography

Sl. No.	Comments	Responses
32	Page 16: “Aqoustic” must be “Acoustic”.	It has been corrected
33	Presumably one of the two last columns of Table 3.2 on page 18 must refer to ebb tide instead of flood tide.	It has been corrected
34	Page 18, Section 3.2.4, line 4: “gradation” must be “spatial distribution”.	It has been corrected
35	The report uses the different terms “groyne”, “groin” and “spur” for the same transverse river training structure. For easier readability it is recommended to use one of the three terms only. The spelling “groin” is correct in the United States of America, but not in Europe and Canada. In Europe and Canada, it is “groyne” that refers to a transverse river training structure, whereas “groin” refers to the part of the body where the two legs meet.	It has been corrected
36	Important places such as Chandgar and Baroaria are missing in the study area map of Figure 2.1. They are also not found in the maps in Figures 3.1, 4.1, 5.1 and 5.2. The first time their locations are shown is in Figure 5.3. It is recommended to show them in the beginning of the report.	It has been corrected
37	The purpose of Section 2.4 is not clear. The formula for the effect of salinity on the settling of sediments does not play any role in the remainder of the report.	Agreed