APPROVED
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FLOOD AND RIVERBANK EROSION RISK MANAGEMENT INVESTMENT PROGRAM (FRERMIP) PROJECT-1

ADB LOAN NO. 3138-BAN (SF) AND GRANT NO. 0396-BAN (EF)

RIVER STABILIZATION AND DEVELOPMENT: JAMUNA-PADMA AND DEPENDENT AREAS

Prepared for:

Bangladesh Water Development Board (BWDB)
Dhaka, Bangladesh

Prepared by:

Institutional Strengthening and Project Management Consultant (ISPMC)

Joint Venture
NORTHWEST HYDRAULIC CONSULTANTS LTD./EUROCONSULT MOTT MACDONALD

Final
6 June, 2020

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FRERMIP
Flood and Riverbank Erosion Risk Management Investment Program

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In association with

DELTARES, RPMC, and CEGIS

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This report forms part of a set of five main reports:

1. *Strategic Framework River Stabilization and Develpoment: Jamuna-Padma and Dependent Areas – an overview report, recommended for approval by the Bangladesh Water Development Board during the third Technical Advisory Committee meeting on 16 September 2017. This report is Supplementary Annex A1.*

2. *The River Stabilization Plan for Jamuna and Padma – a technical document relevant to the implementation of the Plan, recommended for approval by the fifth Technical Advisor Committee meeting on 23 February 2020 and the Main Report as directly relevant to the operations of the Client, the Bangladesh Water Develpoment Board.*

3. *The Preliminary Regional Master Plan for the North-Central Zone of Bangladesh – a planning document that covers the North-Central Zone of Bangladesh dependent on distributary flow and dominated by the capital city of Bangladesh – Dhaka, one of the fastest growing mega-cities in the world. The area was defined as Master Plan area in the Inception Report, accepted by the first Technical Advisory Committee of the Bangladesh Water Development Board on 3 March 2016. This report contains general planning principles relevant at the level of the General Economics Division of the Planning Commission. This report is Supplementary Annex A2.*

4. *The Social and Environmental Assessment for River Stabilization and Development: Jamuna-Padma and Dependent Areas – a strategic approach to address large-scale, cumulative, and potential transboundary environmental and social impacts of the River Stabilization Plan. The Stategic Environment and Social Assessment (SESA) was prepared in parallel with the River Stabilization Plan and reviewed multiple times by the Netherlands Commission for Environmental Assessment between 2016 and 2020 on request of the Project Director Bangladesh Water Development Board. This report is Supplementary Annex A3.*

5. *Inland Navigation – Past, Present, and Future Expectations – an overview of historical and potential future inland navigation along the Jamuna-Padma corridor and associated dredging activities, drawing a high focus of the Bangladesh Government. This report is Supplementary Annex A4.*

The main River Stabilization Plan report is accompanied by nine volumes of supplementary annexes containing 37 individual reports, including the four supplementary annexes mentioned above.

RIVER STABILIZATION PLAN DOCUMENTS

RIVER STABILIZATION PLAN MAIN REPORT

SUPPLEMENTARY ANNEX A: CONTEXT DOCUMENTS

VOL 1 Strategic framework for river stabilization and development: Jamuna-Padma and dependent areas
VOL 2 Preliminary regional master plan for the North-central Zone of Bangladesh
VOL 3 Strategic-environmental and social assessment (SESA) of river stabilization and development: Jamuna-Padma and dependent area
VOL 4 Inland navigation – past, present and future expectations

SUPPLEMENTARY ANNEX B: MORPHOLOGY – GENERAL

VOL 1 Holistic river morphology analysis for the Brahmaputra system
VOL 2 Long term view of channel morphology
VOL 3 Analysis of historical cross-sections of Brahmaputra-Jamuna and Padma Rivers
VOL 4 Char characteristics and dynamics – past and present conditions on basis of satellite images
VOL 5 Upper Meghna – present conditions and issues

SUPPLEMENTARY ANNEX C: MORPHOLOGY – BIFURCATIONS & OFFTAKES

VOL 1 River bifurcations: Theory and modelling experiences
VOL 2 Anabranching channels of the Jamuna and Padma Rivers
VOL 3 Schematic numerical modelling of bifurcations
VOL 4 Reach 3 and bifurcation: numerical modelling
VOL 5 Offtake and flow dynamics of the major rivers
VOL 6 Offtakes part 2: Lessons learned & generic guidelines

SUPPLEMENTARY ANNEX D1: RIVER ENGINEERING

VOL 1 River Stabilization Plan – Technical Basis
VOL 2 River stabilization of other main rivers

SUPPLEMENTARY ANNEX D2: RIVER ENGINEERING

VOL 3 Experience and lessons learned with river stabilization activities in the main rivers of Bangladesh
VOL 4 Future reference planform for Jamuna and Padma Rivers
VOL 5 Feasible techniques for riverbank protection and river stabilization
VOL 6 Underwater apron for Chandpur confluence

SUPPLEMENTARY ANNEX E: FLOOD RISK MANAGEMENT

VOL 1 Main river flood risk and management
VOL 2 Flooding, numerical modelling

SUPPLEMENTARY ANNEX F: RIVER STABILIZATION IMPACTS

VOL 1 Long-term effects of river narrowing on water levels
VOL 2 Effects of sinuosity on channels and bars
VOL 3 River stabilization and sediment management
VOL 4 Modelling of impact of char land sedimentation
VOL 5 Impact of earthquake induced sediment supply variability
VOL 6 Future conditions affecting flows: Climate change and flow regulation

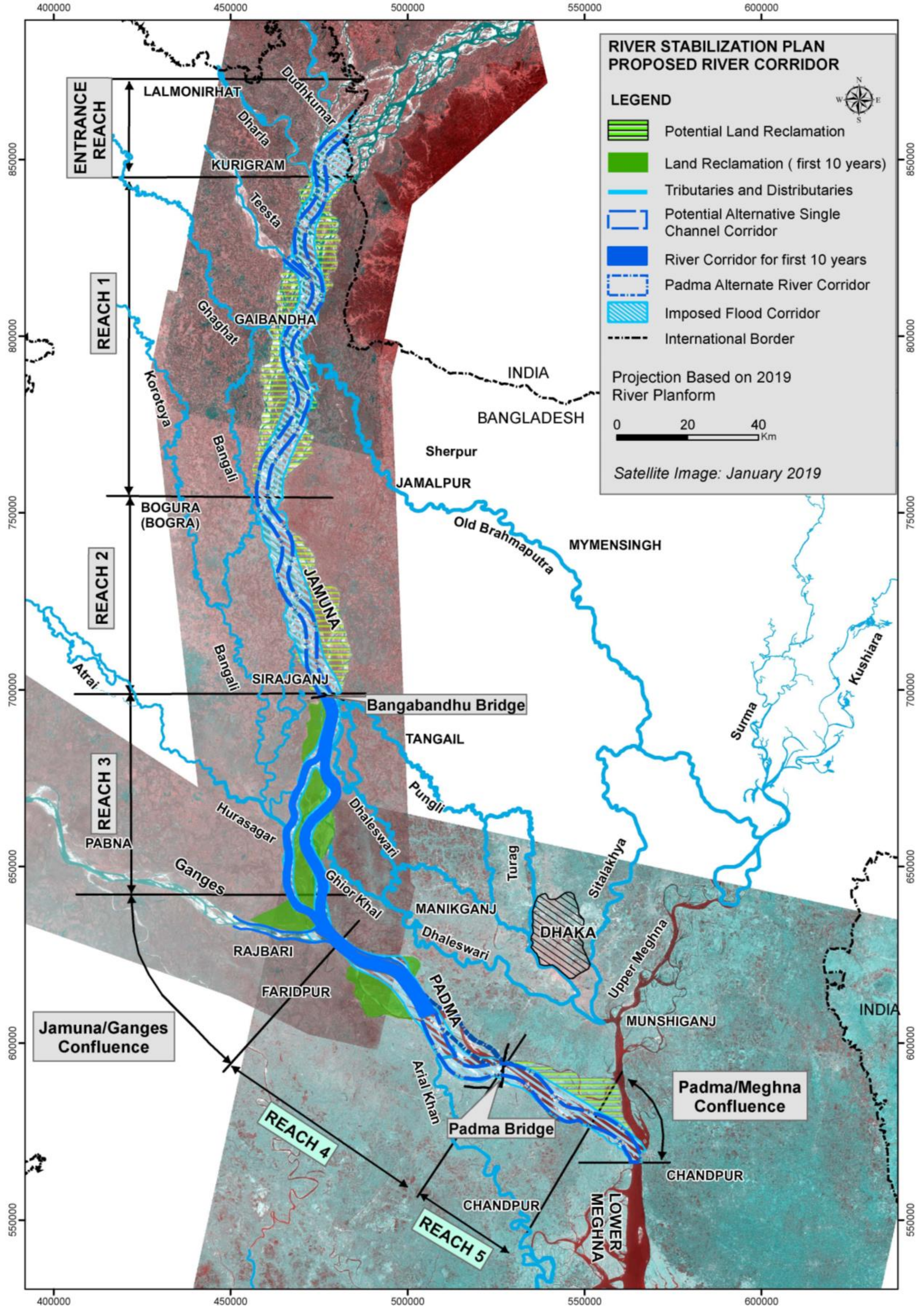
SUPPLEMENTARY ANNEX G: WATER RESOURCES MANAGEMENT

VOL 1 Distributaries: Water resources preparation and baseline
VOL 2 Potential impacts of flow augmentation and study needs

SUPPLEMENTARY ANNEX H: LAND USE & ECONOMIC ASSESSMENT

VOL 1 Social aspects of river stabilization
VOL 2 Environmental and social aspects of river stabilization: impacts and remedial measures
VOL 3 Fisheries impacts and their management: A pre-project status review
VOL 4 Planning the use of stabilized and reclaimed land
VOL 5 Char land amelioration and agricultural development
VOL 6 Economic assessment of river stabilization

Project Document Map



EXECUTIVE SUMMARY

1 Plan Context and Introduction

This River Stabilization Plan is the primary output of knowledge-based activities related to the first phase of the Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP, the Investment Program) implemented by Bangladesh Water Development Board (BWDB) from mid-2014 to mid-2023 with financial support from the Asian Development Bank (ADB) and the Royal Netherlands Government. The FRERMIP River Stabilization Plan addresses the stability of the Jamuna River, from near the Bangladesh-India border downstream to the Jamuna/Ganges confluence, and of the Padma from its origin at the Jamuna/Ganges confluence downstream to the Padma/Upper Meghna confluence.

The Investment Program was designed at a time when Bangladesh had achieved sustained economic growth for over five years of +6.3% GDP per year; poverty had been reduced by one-half in a decade; and significant progress had been made narrowing the gender gap and providing greater access to health and social services. The Government's 2008 Perspective Plan, entitled Vision 2021, set out goals and strategies to transition Bangladesh from a low-income economy to a first-stage middle-income economy by 2021. This goal was achieved in 2015. The Government's Sixth Five Year Development Plan (2011 – 2015) focused on economic growth with equity, social justice, and poverty reduction. Sustainable management of rivers, combined with measures to increase resilience to climate change, was considered essential to addressing these objectives.

In 2004, the Government approved a National Water Management Plan that provided a framework of short, medium, and long-term strategies and eight focal agenda. One of these eight was Main River Development, to which nearly a quarter of the total budget was allocated. The Main River Development agenda encompassed,)

- development of the main rivers,
- water supply,
- a viable and affordable plan to deal with river erosion, and
- hydropower.

Further impetus for FRERMIP was provided by the Disaster Management Act 2012, which promoted a shift from reactive disaster recovery and relief towards proactive preparedness and prevention, of particular relevance to sustainable river management given the high population density and increasing assets on the floodplains.

During the implementation of the FRERMIP phase one, several other river management related studies were undertaken. Each of these studies was considered in the formulation of the FRERMIP River Stabilization Plan. The Bangladesh Delta Plan 2100, approved by Government in 2018, presents strategies and interventions that address long-term water and food security, economic growth, and environmental sustainability, while reducing vulnerability to natural disasters. The Capital Dredging and Sustainable River Management Project (2011 to 2015) was completed, financed by Government. A river stabilization plan for the Jamuna and Padma Rivers, portions of the Ganges River, and its major tributaries (2019) was prepared by Yellow River Engineering Consultants, with Chinese Government support. The Brahmaputra-Jamuna River Economic Corridor Development Plan (2019) was prepared by the Institute of Water Modeling with World Bank support.. And a conceptual plan for stabilizing the Brahmaputra – Jamuna River (2019) was prepared by a joint task force from the

Institute of Water and Flood Management, Bangladesh University of Engineering and Technology and BWDB.

The Problem

The Jamuna and Padma River have undergone significant morphologic changes over time including widening and increased rates of channel shifting, with profound implications for bank erosion, flood embankment damage, and flooding problems along the rivers. Explanations for the widening of the Jamuna River in the 1980s and 1990s have focused on the sediment wave generated by the 1950 Great Assam Earthquake, and the effects of numerous large floods during the period. Likely both of these forcing mechanisms affected channel morphology. An important finding from geomorphic studies is that the river channel expanded to its greatest width in the early 21st century, compared to all other points in the historic record. Future sediment supply and discharge is expected to continue to vary inter-annually, inter-decadally, and over longer time scales, in response to future precipitation, land/water use, and earthquakes in the catchment, and global climate change.

Loss of agricultural land and destruction of infrastructure due to bank erosion and channel widening are significant constraints to development. Embankment failure reduces or nullifies flood protection benefits, resulting in widespread flooding; and embankments weakened by bank erosion and scour often fail at water levels well below design. High population density, combined with the extent of flood-prone areas, prevents Bangladesh from restricting settlement in high-risk areas. Higher flood risk floodplain areas tend to be poorer, and the cost of flood disaster mitigation increases with increasing flood risk.

River Stabilization Plan Goals, Objectives, and the Need to Manage Uncertainty

The Bangladesh Delta Plan 2100 (2018) states that many of the water-related challenges in the country relate to the major rivers, and that the major rivers have national importance since they are the backbone of the delta system. The River Stabilization Plan goals correspond to Delta Plan strategies for dealing with the major rivers:

- (i) Provide adequate room for the river and infrastructure to reduce flood risks.
- (ii) Improve conveyance capacity as well as stabilize the rivers.
- (iii) Provide fresh water of sufficient quantity and quality particularly through the improvement of distributaries.
- (iv) Maintain ecological balance and values (assets) of the rivers.
- (v) Promote safe and reliable waterway transport in the river system.
- (vi) Develop strategy for sediment management, adopting natural processes as well as dredging and char land development.
- (vii) Strengthen river and estuary management in the newly accreted lands and land use planning.

To achieve these goals, the River Stabilization Plan addresses the following objectives:

- (i) Provide a stabilized planform.
- (ii) Recover land made available by a narrower river corridor.
- (iii) Stabilize offtake locations.
- (iv) Ensure a more stable and deeper dry season navigation channel.

The River Stabilization Plan acknowledges, and proposes an adaptive approach to manage, a range of major uncertainties in driving forces and trends relevant to river management planning – uncertainties that arise in turn from limitations in data about, and in the predictability of, climatic, hydrological, morphological, and socio-economic processes (also refer to The Bangladesh Delta Plan, GED, 2018).

Planning Approach and Strategy

The adaptive approach proposed here to manage the range of uncertainties consists of a comprehensive river stabilization plan developed and implemented over several decades, that accommodates future changes in river behaviour, incorporates experience gained during the implementation process, and allows for on-going research on river response to stabilization measures.

The strategy is to implement the plan in a series of relatively short planning and investment cycles (ten years and five years respectively, the latter for consistency with Government's five-year planning process). This will allow planners to take into account events and learning as they occur, rather than planning the entire infrastructure program from one set of early long-term river behavior predictions, that are at high risk of becoming obsolete while implementation is still in progress.

The River Stabilization Plan

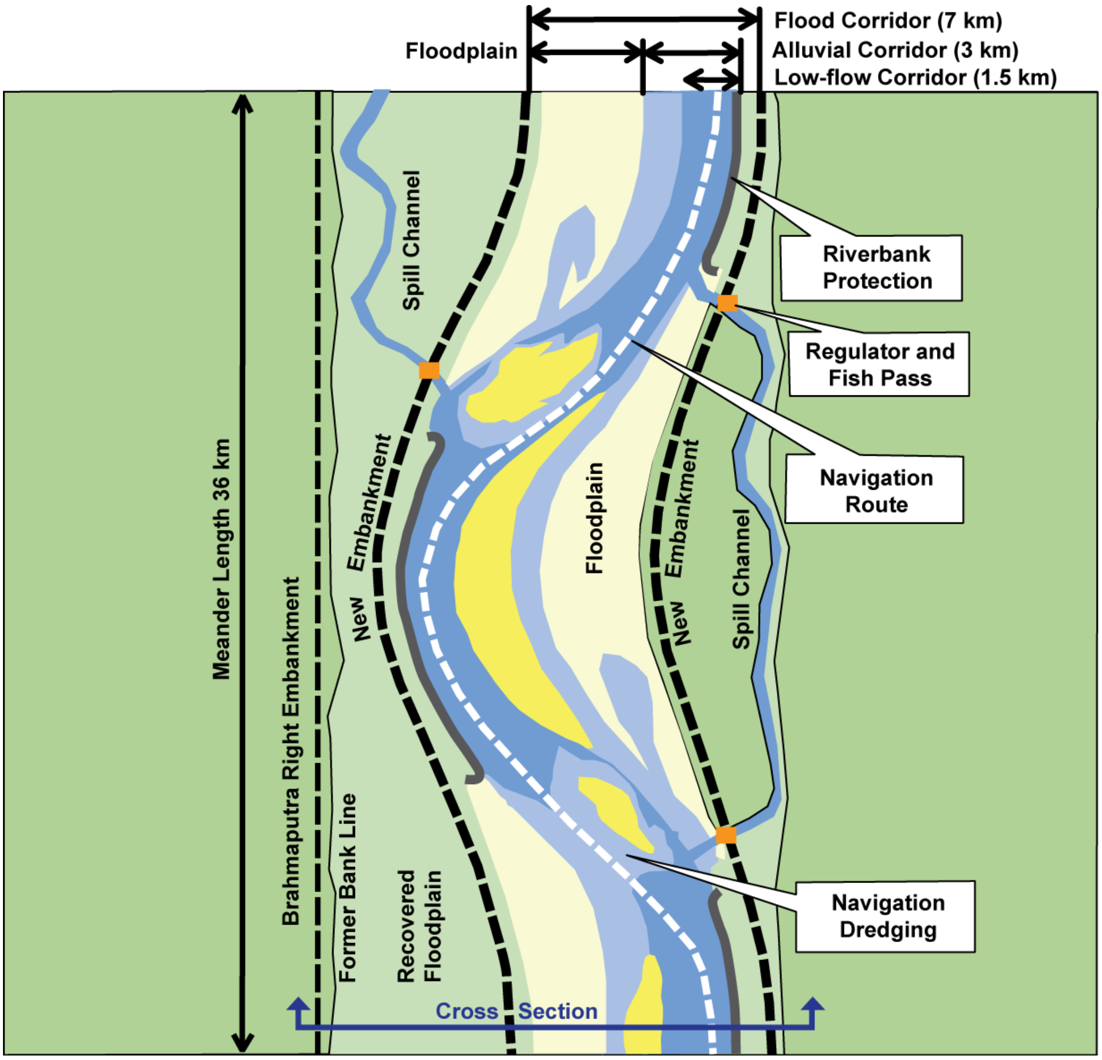
The River Stabilization Plan adopts the concept of managing future floods and morphological changes within a dynamic, stable river corridor. Maintaining the stabilized corridor will allow:

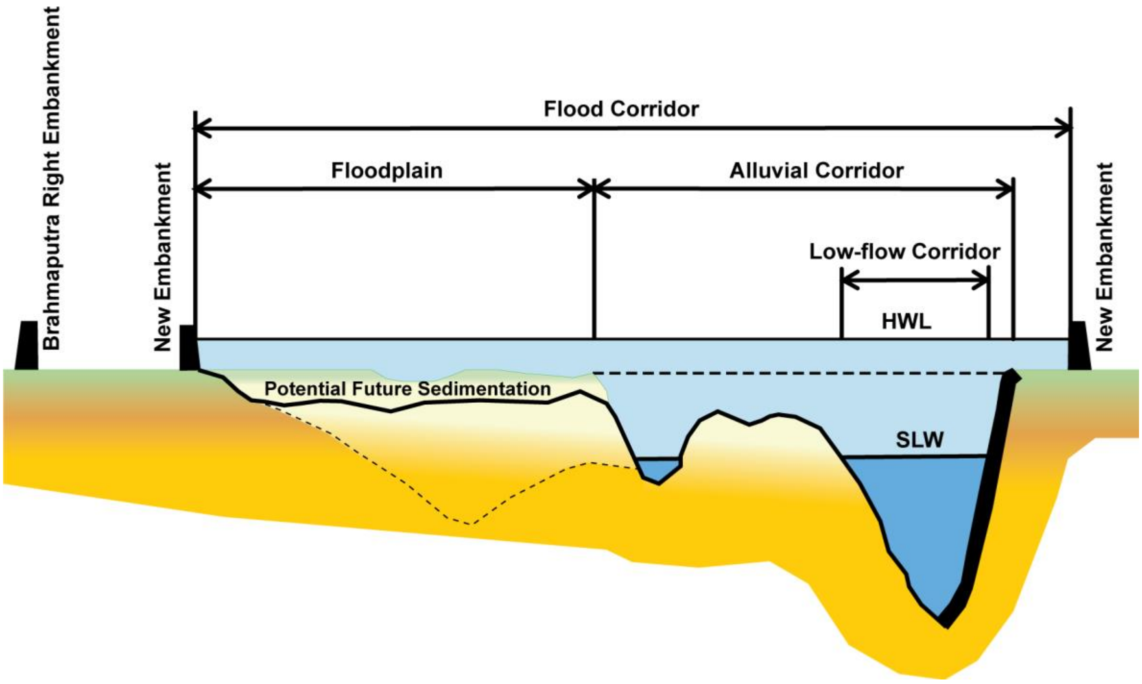
- Improved reliability of flood protection embankments.
- Improved water supply and water quality along major distributary channels to the surrounding region.
- Improved inland water transportation both in the main rivers and distributary channels.
- Recovery of some floodplain land lost to erosion during the last half century.

Transforming the river's planform and limiting its range of migration while still maintaining a dynamically stable alluvial channel will be an unprecedented engineering challenge. Most experience on smaller, less morphologically active rivers is not transferrable to the situation in Bangladesh. No other river has a comparable set of physiographic, geologic, and hydrologic parameters. Consequently, pilot testing of concepts and "learning by doing" will be critically important steps in developing and verifying stabilization concepts and designs.

The river management corridor consists of two parts - a dynamically stable alluvial corridor that conveys most of the river's sediment and a wider flood corridor that can safely convey extreme floods (see figure below for the example of a dominantly single channel planform).

The extent of the flood corridor is defined by the distance between the new or existing flood embankments along the riverbank. The entire area within the flood corridor might be reworked by erosion, some areas frequently (the river or alluvial corridor) and some areas only sporadically (the flood corridor). Preliminary estimates for the dimensions of the corridor are presented in the table below.


Floodplain
Flood Corridor (7 km)
Alluvial Corridor (3 km)
Low-flow Corridor (1.5 km)
Meander Length 36 km
Brahmaputra Right Embankment
Former Bank Line
Recovered Floodplain
Spill Channel
New Embankment
Floodplain
New Embankment
Spill Channel
Riverbank Protection
Regulator and Fish Pass
Navigation Route
Navigation Dredging
Cross Section


Brahmaputra Right Embankment
New Embankment
Flood Corridor
Floodplain
Alluvial Corridor
Low-flow Corridor
HWL
Potential Future Sedimentation
SLW
New Embankment

River	Alluvial Corridor Width (km)	Flood Corridor Width (km)
Jamuna	3	6.0 to 6.5
Padma	4	8.0 to 10

It is expected that these dimensions will be refined and modified as new information becomes available during the subsequent phases of the project. Therefore, the dimensions are considered as tentative estimates rather than as final design parameters.

The method of bend control has been adopted as the preferred approach for stabilizing the overall alignment and planform of the rivers. This approach limits the overall length of bank protection to approximately 30% to 60% of the total reach length and also allows for some dynamic adjustment of the channel pattern and channel alignment. Adopting this method does not necessarily require confining all sections of the river into a single, narrow meandering channel. In some reaches it will be feasible to establish or maintain a single channel. In other sections, an anabranched planform may require less maintenance and be more stable in the long-term. The river training measures will consist of long guiding revetments. One of the principle functions of these structures will be to promote the formation of a more stable channel pattern even when only built along parts of the riverbank. The training structures will be constructed primarily using geobags due to their proven performance and lower cost.

The time frame and the specific actions required to fully implement the plan and achieve the Plan's goals will depend to some degree on the future trends in water and sediment loads that are experienced. These inputs are the main hydro-geomorphic controls that govern the river's stability and channel pattern. The dynamic, adaptive nature of the Plan allows for modifying the implementation pathways to account for different future scenarios while still meeting the goals and objectives.

Implementation of the Plan

Because of uncertainties associated with forecasting natural river processes and upstream basin developments as well as the river response to systematic stabilization, this section proposes an implementation plan for the first ten years of the investment program.

During the initial ten years, systematic river stabilization will focus on the Jamuna River from Bangabandhu (Jamuna) Bridge to the confluence of the Ganges and on the Padma River from the Ganges confluence to Padma Bridge. These two reaches have a river pattern that is close to the desired pattern. Stabilizing the river in these two reaches is achievable and will develop an understanding and skillset for the more difficult work in the upstream reaches. During initial implementation in these two reaches, acute erosion problems in other reaches will be addressed as per present day standards before commencing systematic stabilization of these reaches.

The investment costs for the work over a period of 10 years are estimated to be BDT 7,250 Crore or US$ 840 million. An additional 30% of this amount would be required for land acquisition, resettlement, other development works, knowledge-base development, and project management.

Potential Plan Impacts

A Reference Project was formulated to represent one plausible long-term future scenario which considers continued reduction of incoming sediment loads, allowing establishment of a channel narrower than what existed in the last 20 to 30 years. The economic, environmental and social impacts that are presented in the Plan are based on the Reference Project.

Economic Impacts

Based on the reference scenario, annual net economic benefits are expected to result from flood mitigation, char land development, as well as improved navigation and road transportation. The annual net economic benefits are estimated at BDT 1,947 billion (USD 22.9 billion). Given that the 2019 GDP of Bangladesh was about BDT 26,690 billion (USD 314 billion) the economic value added by the River Stabilization Plan is significant. The following table summarizes the annual net economic benefits.

Intervention	Annual Net Economic Benefits		
	BDT M	USD M	% of total
Flood Mitigation	**22,363**	**263**	**1.1%**
Reduced Damage	*15,945*	*188*	*0.8%*
Incremental Agriculture	*6,418*	*76*	*0.3%*
Char land development	**1,905,202**	**22,414**	**97.9%**
Rural Settlements	*35,627*	*419*	*1.8%*
Economic Zones	*1,869,575*	*21,995*	*96.0%*
Road Transport	**6,517**	**76**	**0.3%**
Navigation	**12,710**	**150**	**0.6%**
Total	**1,952,386**	**22,902**	**100%**

Social and Environmental Impacts

At this early stage of project planning and implementation, social and environmental impact assessment emphasizes the identification of potentially significant impacts (“scoping”). Additional environmental and social impact investigations and the development of impact management measures will be undertaken during each future stage of planning and implementation, with the ultimate objective of achieving project outcomes that are environmentally and socially acceptable. The table below lists the potential environmental and social impacts of the Reference Project identified in Strategic Environmental and Social Assessment (SESA).

Potential Environmental and Social Impacts, Reference Project (based on SESA 2020)		
Activity	**Positive**	**Negative**
Construction phase impacts of engineering works & dredging		•Air/water emissions and solid waste pollution •Energy used and carbon dioxide emitted •Construction disruption of transportation, land use •Aquatic biota impacts of suspended sediment from dredging •Spoil disposal site impacts •Labor force movement, presence etc. impacts

Erosion control & planform stability river	• Stabilized Flood Corridor • Reduced erosion, riverbanks & Corridor floodplain zone • Expanded deeper river habitats used by some river fish species & Ganges River dolphin *Platanista gangetica* • Protected areas demarcated more readily at stabilized land-water boundaries	• Extirpation of Low Flow Corridor char land, all residents, users displaced • Reduced temporary wetland area used by benthic fauna & fish spp • Reduced area of sand/gravel islands used for bird breeding some spp • Geobag decommissioning impacts, not well understood, likely benign
Stabilizing & raising levels of char lands	• Conversion of low-lying, fragmented char areas to larger highland parcels	• Temporary / permanent displacement of char land inhabitants, users, & biodiversity where dredge spoil is dumped & reeds planted
Flood embankments and associated structures	• Reduced seasonal flooding of agricultural land, aquaculture, settlements, infrastructure (etc) • Reduced damage to crops and property	• More frequent and deeper flooding, esp. higher maximum flood levels in Flood Corridor affecting inhabitants and users of (a) Alluvial Corridor chars outside the Low Flow Corridor & (b) Floodplain zone chars. Some inhabitants & users will leave; remainers must manage • Potential adverse effects of lower low water levels in the main river, including: reduced flow into distributaries; accelerated scouring at river engineering works; impediments to navigation at main river - small navigable channel junctions; Bangladesh-India border impacts • Biodiversity impacts of reduced river-floodplain aquatic connectivity • In flood-protected area, declining surface water coverage, ground water levels, water transport; local rainfall drainage congestion • in flood-protected area, decreased floodplain wetland area & duration with adverse effects on biodiversity & fish production
Offtake engineering works & distributary dredging	• Increased low flows & regulated flood flows in distributaries • Improved water supply / quality to Planning Region including Dhaka & distributary-connected wetlands • Enhanced biodiversity in distributaries & their wetlands	
Navigation dredging	• Enable reliable container traffic from Planning Region to sea	
Knock-on impacts of engineering works & dredging on land-based economic activities	• Accelerated economic-social improvement via enhanced investment opportunities in more secure environment • Availability of newly-stabilized highland parcels to meet various policy goals eg industrial development; poverty reduction; more secure livelihoods for vulnerable char and river bank populations including through redistribution of khas land to landless and poor marginal farmers; agricultural intensification and promotion of commercial farming; improved wetland protection • Reduced disaster management costs	• Potential negative impacts of accelerated economic development include increasing pollution, increased energy use, carbon emissions etc
Biodiversity mitigation & enhancement	• Establishment of protected areas along the Padma-Jamuna, including river fish sanctuaries and conversion of lower-biodiversity char areas to higher-biodiversity protected areas • Placement of buoys to reduce drift net use	

ACRONYMS / Glossary

ADB	Asian Development Bank
BDT	Taka (currency of Bangladesh)
BIWTA	Bangladesh Inland Water Transport Authority
BUET	Bangladesh University for Engineering and Technology
BWDB	Bangladesh Water Development Board
CBJET	China Bangladesh Joint Experts Team
CEGIS	Centre for Environmental and Geographic Information Services
DPP	Development Project Proforma
EZ	Economic Zones
FAP	Flood Action Plan
FRERMIP	Flood and Riverbank Erosion Risk Management Investment Project
GIS	Geographical Information System
GoB	Government of Bangladesh
IWFM	Institute of Flood and Water Management, BUET
IWM	Institute of Water Modelling
JMREMP	Jamuna-Meghna River Erosion Mitigation Project
M	Million
MDIP	Meghna Dhonagoda Irrigation Project
PIRDP	Pabna Irrigation and Rural Development Project
PPTA	Program Preparatory Technical Assistance
RBIP	River Bank Improvement Project
RRI	River Research Institute
RSP	River Stabilization Plan
SESA	Strategic Environmental and Social Assessment
SPP	Species Pluralis (Multiple Species)
USD	United States Dollar
WARPO	Water Resources Planning Organization
WB	World Bank

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PART ONE – INTRODUCTION

1 CONTEXT

The River Stabilization Plan (RSP) forms a central part of the knowledge-base development activities of the first phase of the Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP). The FRERMIP is implemented by the Bangladesh Water Development Board with financial support from the Asian Development Bank and the Royal Netherlands Government. The latter provided the grant funding for most of the RSP preparation. FRERMIP was scheduled to be implemented over a period of nine years from mid-2014 to mid-2023.

2 THE RIVER STABILIZATION PLAN

2.1 Key Facts

Name: River Stabilization and Development, Jamuna-Padma and Dependent Areas

Country: Bangladesh

Location: Jamuna-Padma river corridor from the Indian border to Chandpur; dependent areas delineated by the river flood affected areas on the Jamuna and Padma right banks, and the North-central Zone on the left banks affected by river floods as well as supplied during the dry season through the distributary systems of Old Brahmaputra and Dhaleswari rivers.

Agencies
Lead: Bangladesh Water Development Board (BWDB)
Associated: Bangladesh Inland Water Transport Authority**;** Ministries of Land, Industry, and Agriculture; Bangladesh Economic Zones Authority

Funding: Estimated USD 7.26 billion or BDT 617 billion (in 2019 prices)

Goals:

1. Provide adequate room for the river and infrastructure to reduce flood risks;
2. Improve the conveyance capacity as well as stabilize the rivers;
3. Provide fresh water of sufficient quantity and quality particularly through the improvement of distributaries;
4. Maintain ecological balance and values (assets) of the rivers;
5. Promote safe and reliable waterway transport in the river system;
6. Develop strategies for sediment management adopting natural processes as well as dredging and char land development; and
7. Strengthen land use planning and river and estuary management in the newly accreted lands.

Objectives:

1. A stabilized planform;
2. Land recovery in a narrowed corridor;
3. Stable offtake locations; and
4. More stable and deeper dry season navigation channels.

Approach: The RSP principles plan on recurring five-year investment programs that are in line with the Government's Five Year Plan cycle. For each investment cycle, a detailed program of interventions will be developed that incorporates the changes in river response to prior investments. Main activities in the short term (until 2030) focus on systematic stabilization of Reaches 3 and 4, continuous collection of core river data, address erosion issues in the remaining reaches on an as-need basis, and prepare stabilization strategies for Reaches 1, 2 and 5. Main activities in the mid-term (until 2050) focus on stabilization of Reach 5 and preparing for interventions in Reaches 1 and 2. Depending on the river morphology, Reaches 1 and 2 might extend to the end of this century.

2.2 Background to the River Stabilization Plan

The Investment Program, FRERMIP, was designed when Bangladesh had achieved sustained economic growth (GDP) of 6.3% per year for over five years, poverty had been reduced by one half over that of a decade earlier, the gender gap had narrowed, and the country had made progress in providing access to health and basic social services. The Government's 2008 Perspective Plan entitled "Vision 2021" had set out goals and strategies that were destined to transition Bangladesh from a low-income economy to the first stage of a middle-income economy by 2021. This goal was achieved in 2015. The Government's sixth Five Year Development Plan (2011 – 2015) focused on economic growth with equity, social justice, and poverty reduction. Sustainable management of rivers combined with measures that increase resilience to climate change were considered essential to accomplishing the growth and poverty reduction objectives.

In 2004, the Government approved a National Water Management Plan that provided a framework for short, medium, and long-term strategies. This Plan presented eight focal agenda. Main River Development, with an allocation of nearly 25% of the total cost, was one of these eight. The Main River Development agenda encompassed development of the main rivers, fresh water supply, a viable and affordable plan to deal with the river erosion problem, and hydropower.

Further impetus for FRERMIP was provided by the Disaster Management Act 2012, which promoted a shift from reactive recovery and relief towards proactive preparedness and prevention. This was particularly important given the high population density and increasing assets on the floodplains.

Since FRERMIP was initiated, the Bangladesh Delta Plan 2100 was completed and in 2018 approved by the Government. This Plan presents strategies and interventions to ensure long-term water and food security, and economic growth and environmental sustainability while reducing vulnerability to natural disasters. As well, the Government financed the Capital Dredging and Sustainable River Management Project (2011 to present); with Chinese Government support the Yellow River Engineering Consultants prepared a river stabilization plan for the Jamuna and Padma Rivers, portions of the Ganges River and major tributaries (2019); a joint Institute of Water and Flood Modeling (IWFM), Bangladesh University of Engineering Technology (BUET) and BWDB task force prepared a conceptual plan for stabilizing the Brahmaputra – Jamuna River (2019); and, the Bangladesh Institute for Water Modelling (IWM) submitted the Brahmaputra-Jamuna River Economic Corridor Development Plan (2019). The foregoing studies were considered in the approach and formulation of this RSP prepared under FRERMIP.

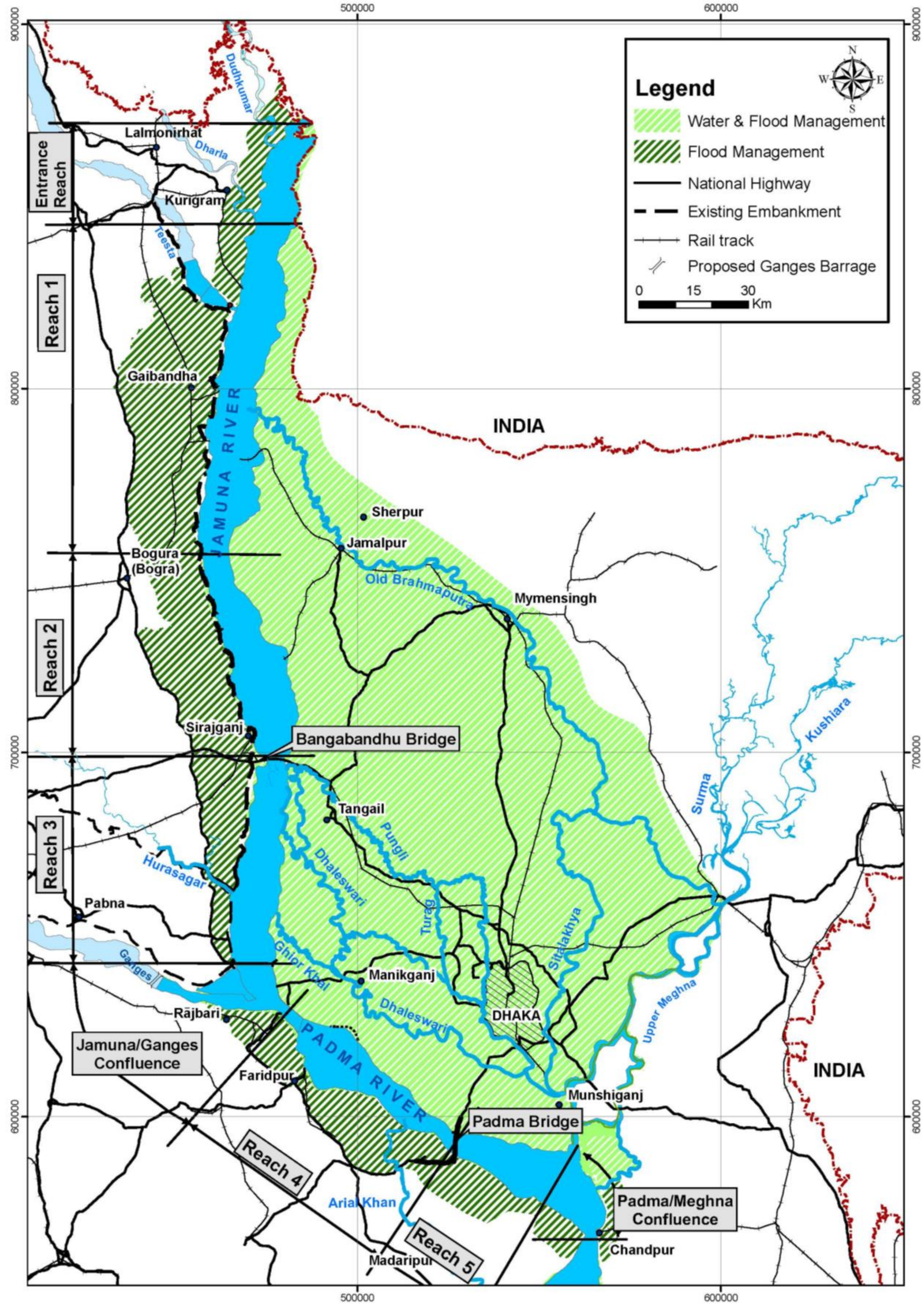

Figure 1: Map of RSP Area (ISPMC).

2.3 River Stabilization Plan Region

2.3.1 River Reaches

The RSP addresses river stability of the Jamuna River from near the border with India and extending downstream to its confluence with the Ganges River, and the Padma River from its beginning at the Jamuna/Ganges confluence and extending downstream to the Padma/Upper Meghna confluence.

2.3.2 Potential Impact Area

The area potentially impacted by RSP interventions comprises, in addition to the rivers themselves, an area that extends on average about 15 km west of the right bank of the Jamuna and Padma Rivers. On the left bank of these rivers, the impacted area extends eastward to slightly past the Old Brahmaputra River and southward to the Meghna River following the right bank of the Meghna River to its confluence with the Padma River (Figure 1).

3 THIS REPORT

This summary report provides an overview description of the RSP region's physical and human geography; presents a detailed discussion of the key features of the physical setting; explains why erosion matters; identifies RSP goals, objectives and uncertainties; and reviews past and potential riverbank stabilization strategies. Much of this material has been selected and condensed from reports and technical notes produced by FRERMIP and others. The recommended adaptive long-term RSP, its potential impacts, and how its initial years will be implemented are then described.

The full list of FRERMIP final reports appears in the front of this document. The planning documents are structured in nine volumes consisting of one main report and eight supplementary annexes comprising 37 supporting study reports:

- Main Volume: River Stabilization Plan.
- Supplementary Annex A: Context documents.
- Supplementary Annex B: Present day knowledge and understanding of the river environment.
- Supplementary Annex C: The functioning of river bifurcations and their role in stabilizing a braided/anabranched river.
- Supplementary Annex D: Technical solutions to address river instability and experience with river stabilization.
- Supplementary Annex E: Flood risk assessment and flood modelling for a wide number of future scenarios.
- Supplementary Annex F: Uncertainties and potential impacts of river stabilization.
- Supplementary Annex G: Assessment of water management issues for the North-central Zone.
- Supplementary Annex H: Environmental and social implications, and economic assessment.

4 THE ADAPTIVE APPROACH

To accommodate the range of possible future conditions with which the plan must contend, the Dynamic Adaptive Policy Pathways approach (DAPP, Haasnoot et al., 2013) was used as a conceptual tool to explore and illustrate the potential structure of adaptive plan implementation. This approach is consistent with the principles of Adaptive Delta Management that have been adopted for large-scale water management planning in the country (Bangladesh Delta Plan 2100, GED, 2018).

This summary report also documents a Reference Project which illustrates one potential realization of the adaptive approach.

An adaptive approach was adopted for river stabilization for the following reasons:

- A comprehensive river stabilization plan will need to be implemented over a period of several decades under highly variable hydro-morphological conditions. The plan will need to accommodate future changes in river behaviour, future internal and external developments and experience learned from implementing pilot projects, and further research on how the river responds to stabilization measures.
- Identifying the most appropriate river stabilization strategies and defining a path forward for implementing the plan over a relatively short planning cycle (ten years) is likely to be more useful than preparing a detailed list of structures for the final completed project under an assumption that the river will remain unchanged from present conditions over a period of several decades.

The main components of the planning process are as follows:

- An overview of the region, constraints to the present and future development, and the objectives of the plan: The purpose of this section is to define what a "successful" plan could accomplish, including indicators or targets that will be used to evaluate the performance of the future actions.
- A description of the uncertainties that will play a role in deciding future actions and outcomes: These uncertainties include uncertainties in the future (such as climate change, sediment/water inflows, technological changes) and also the uncertainties in the available data and in our ability to predict future river response and impacts resulting from our actions.
- An analysis of the present and potential future problems, including identifying vulnerabilities and opportunities: In this context, opportunities are future developments that help in achieving the plan's objectives. Vulnerabilities are developments that impair achieving the plan's objectives. These include project assumptions which might not be fulfilled as well as uncertainties associated with the performance of the project and its resulting impacts. This step also includes defining the most critical drivers (external factors that are impacting the region) and a set of future scenarios.
- Identification of possible actions that can be taken to meet the Plan's objectives.
- Evaluation of the actions for each future scenario, identification of when the actions will no longer meet the Plan's objectives (so-called "tipping points"), and evaluation of other pathways that will need to be followed.
- Adaptive plan design, including short-term actions and longer-term options, strategies, and monitoring programs that are needed to update/re-assess the Plan.

The Dynamic Adaptive Policy Pathways (DAPP) methodology can be applied rigorously to produce a complex series of pathways and a quantitative assessment of alternative actions. However, here the main focus is on using the DAPP approach to develop a relatively simple, logical narrative that outlines a realistic adaptive program for stabilizing the river.

PART TWO – CONTEXT AND RATIONALE

5 PLANNING AREA BASELINE ENVIRONMENT

5.1 Physical Environment

The planning area has a three-season sub-tropical monsoon climate. The March-May summer/pre-monsoon and the June-October monsoon seasons are hot and humid, and account for almost 90% of annual rainfall. Winter (November-February) is predominantly cool and dry.

The area is flat and slopes from northwest to southeast. Adjacent to the major rivers are belts of unstable alluvial land that is continuously formed and eroded by the shifting rivers. In consequence, many locations are occupied by ridges and depressions. The predominant floodplain land use is agriculture, with the remaining land used for settlement, homestead forestry, bamboo plantation, chars (river islands/shoals), and water bodies. Chars are typical of braided river systems, in which the sedimentation and erosion process causes char number, location, extent, and height to vary over time. Local people state that RSP area chars range in age from five to 100 years old.

The hydrological network consists of the international main rivers – a network of interconnecting tributary and distributary channels, ranging in size from large to small (khals) – and seasonal and perennial wetlands. The most important distributaries for conveying water to areas away from the main rivers are the Old Brahmaputra and the multiple Dhaleswari channels.

Jamuna discharge is derived from monsoon precipitation, base flow and snow melt. The hydrology of almost 40% of Bangladesh floodplains is Influenced by the Jamuna River. Very high Jamuna water levels cause large-scale flooding (i.e. the exceptional floods of 1954, 1974, 1984, 1987, 1988, 1998, 2004, and 2017). The Padma River carries the discharge of the Jamuna and the Ganges Rivers below their confluence.

Physical processes of key significance to river stabilization are described in detail in Section 6, which covers sediment inflows, water inflows, the river system, channel instability and widening, and flooding and erosion.

5.2 Biodiversity

The planning area contains significant habitat and species-level biodiversity in ecosystems both aquatic (perennial and seasonal flowing water, standing water bodies, and wetlands) and terrestrial (village, crop field, grassland, reed, above-flood level island).

Biodiversity assets of the planning area include large numbers of wild plant and animal species, globally and nationally vulnerable species such as Ganges River Dolphin *Platanista gangetica*, migratory bird staging areas, and tropical floodplain fish habitat. The area contains two dolphin sanctuaries south of the Bangabandhu (Jamuna) Bridge that were declared in 2013, a number of mostly floodplain community-based fish sanctuaries, and three older protected areas (Bhawal National Park, Bangabandhu Sheikh Mujib Safari Park, and Madhupur Reserved Forest; see Figure 2). Two migratory bird sanctuaries in the lower Ganges north of the bridge were proposed some years ago, but have not yet been established.

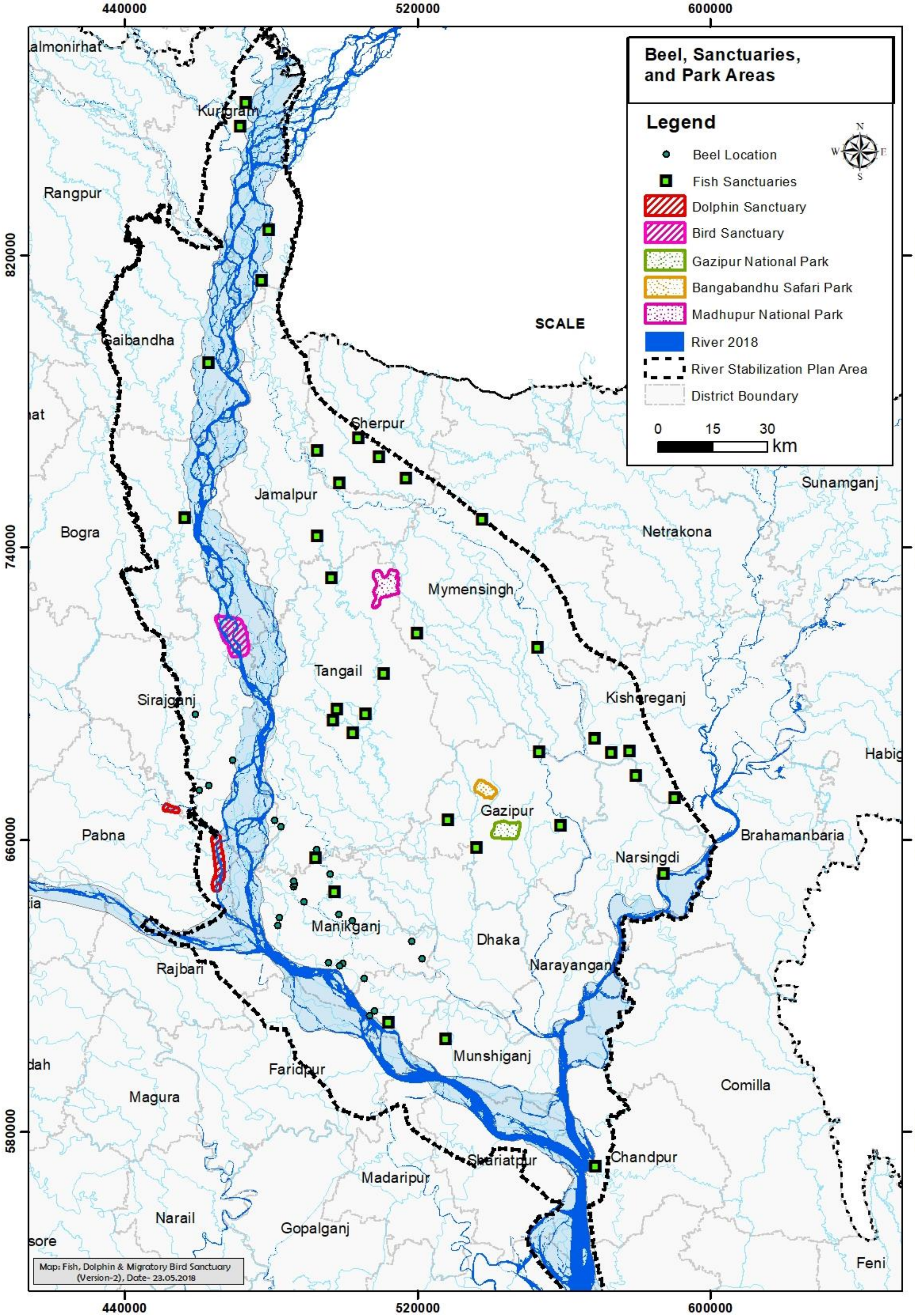

Figure 2: Beels, sanctuaries and parks in the RSP area (ISPMC).

5.3 Socioeconomic Baseline

5.3.1 Population

In the 2011 census, the RSP river corridor (defined as the 485 unions adjacent to the RSP river reaches) had a recorded population of 12.7 million, of which 7.6 million were on the right bank and 5.1 million on the left. The most populous districts on the right bank are Sirajganj, Kurigram, and Gaibandha, and on the left bank, Tangail and Jamalpur (Figure 3).

While historical population data do not provide an estimate of the char population, the union-wide breakdown in 2011 allows a first estimate (Figure 4). Based on unions dominantly in the river corridor, the current population has been estimated to be around 1.8 million. Given the significant amount of area occupied by channels and low-lying sand bars, the population density on chars is not much lower than the average population density of Bangladesh. Annual changes in the available land area within the river corridor lead to some variability of the population density on a year-to-year basis.

The floodplain population density is on average some 50% higher than the average Bangladesh population. When calculating the area lost to erosion with the population density over time, more than 2 million people have likely lost their homes over the last 50 years. This number exceeds the total number of char inhabitants today. Population statistics may not fully reflect population lost to outmigration after erosion of mainland agricultural and village lands; mainland erosion refugees tend to outmigrate inland or to cities rather than to char lands.

At this stage of the RSP, a preliminary rough estimate for the population potentially affected in some way by RSP implementation is 3 million. This estimate encompasses individuals that might be positively impacted by improved flood control and reduced river erosion, as well as those that might be negatively impacted by embankment land acquisition, construction activities, or the adverse impacts of operation, maintenance, and abandonment of project-created infrastructure.

5.3.2 Socioeconomic Profile

Households along embankments, close to the river, and living on chars tend to be more vulnerable than in those in areas less exposed to erosion and flooding. Many such households have lost land, housing, and possessions to the rivers, and rely on support from extended family members, and neighbors. Agriculture is the predominant source of livelihood, with two-thirds of households reporting agricultural income, though the overwhelming majority of households (95%) are landless. Almost half of households have moved at least once due to erosion, and one in twelve have had to move six or more times for this reason. One-fifth of households are deemed extremely poor. Three-quarters of adults have had no formal schooling, but almost half are literate, with women's literacy only slightly lower than men's. Three-fifths of school-age boys attend school, as do half of school-age girls (NHC, 2013; Fichtner and NHC, 2015; Conroy et al., 2010; and Supplementary Annex A3 SESA local stakeholder consultations).

Compared to mainland residents, char dwellers have more limited access to healthcare, education, markets (both to buy agricultural inputs and to sell farm products), government institutions, infrastructure, and off-farm employment opportunities. In the char lands, local elites exercise considerable political control through stable lines of patronage and deeply entrenched social and cultural norms. Char dwellers are the most food insecure in Bangladesh and often experience hunger from September to November. Char dwellers, however, prefer the relatively sparsely inhabited chars to mainland population pressures, and do not readily relocate to the mainland (Schmuck-Widmann, 1996).

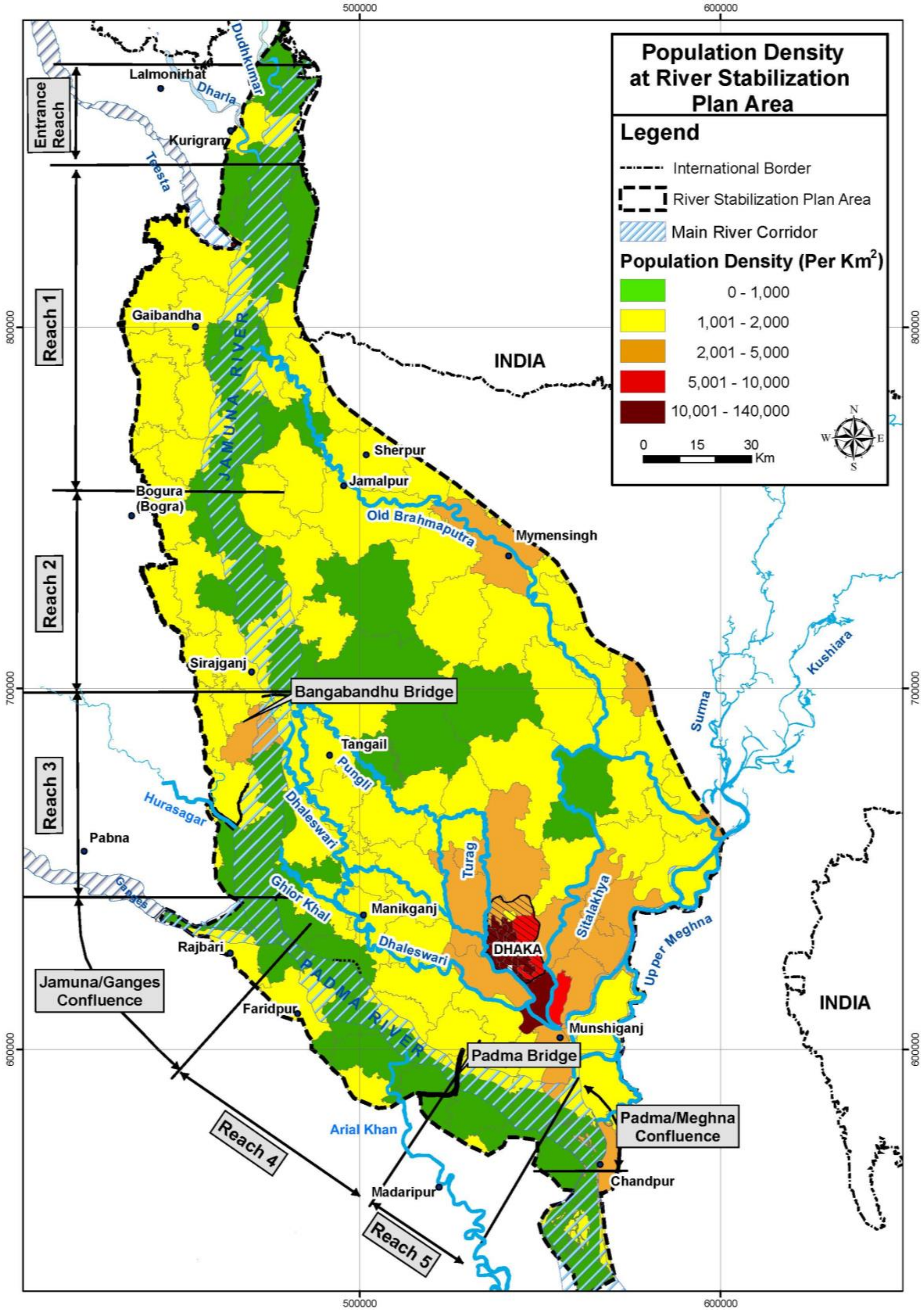

Figure 3: Population density in the planning region (ISPMC).

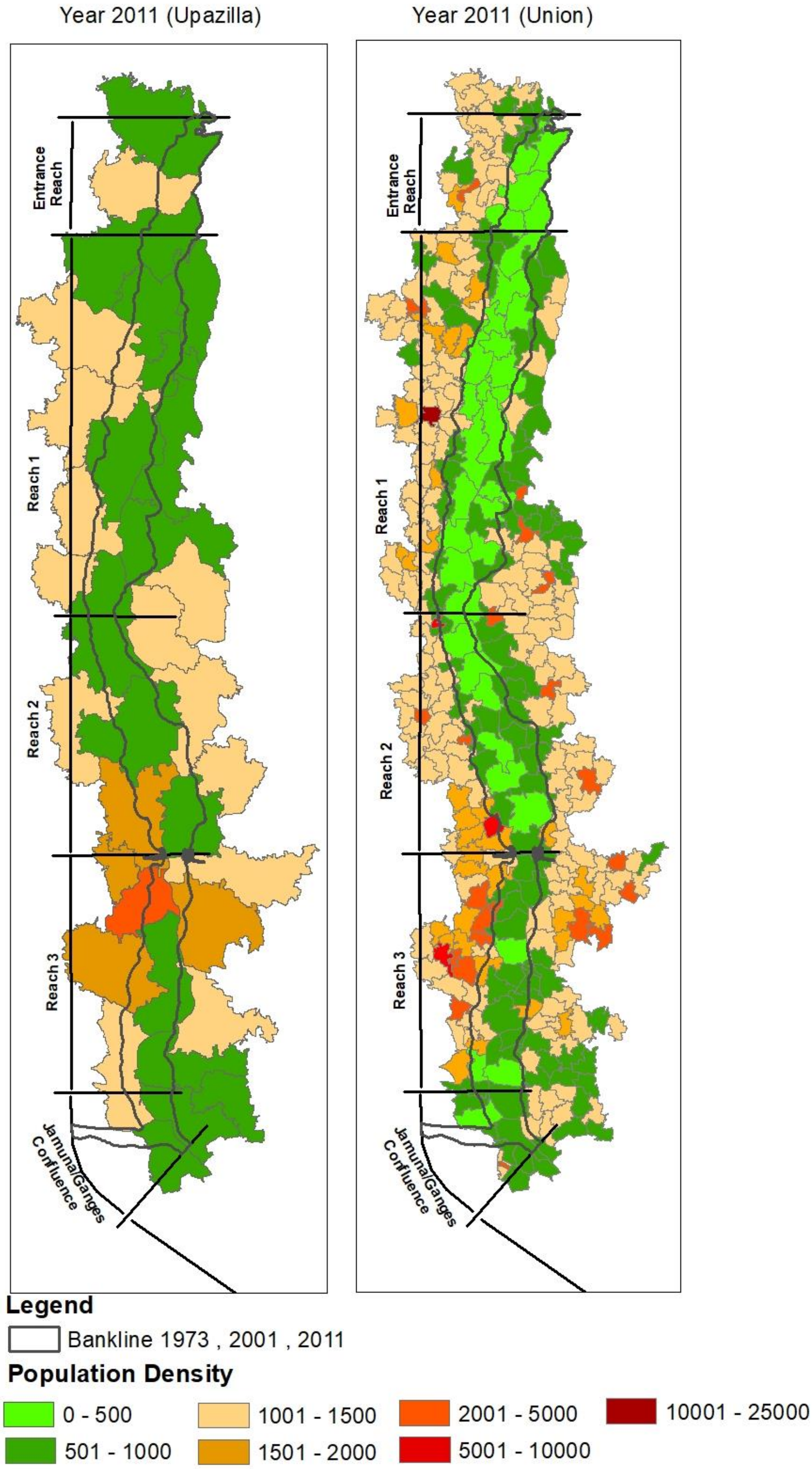

Figure 4: Population density within the Jamuna River corridor (ISPMC).

6 KEY PHYSICAL PROCESSES

The shape, size, and pattern of lateral instability of the Ganges, Jamuna, Padma and Lower Meghna Rivers respond dynamically to the variability of the water and sediment inputs. An understanding of the quantity of sediment delivered to the river and the quantity and timing of water inflows are therefore crucial foundations for managing the river. River management is made more challenging since virtually all of the inflow of water and sediment to the main rivers is generated outside of Bangladesh in the headwaters of the Brahmaputra and Ganges Rivers. This makes it more difficult to plan for future changes as a result of external developments such as flow regulation from dams, water diversions or upstream land use changes.

6.1 Sediment Inflows

Estimates of annual sediment loads on the Jamuna River have varied widely and are very uncertain. Part of the uncertainty arises from the difficulty of collecting systematic, reliable measurements on large rivers and the potential errors and the inaccuracies that can arise in estimating annual loads from a limited number of daily measurements collected over the year. In order to use the data to develop annual sediment budgets or to relate the loads to deposition and erosion processes, the sand load and fine sediment load (silt/clay) need to be estimated, which can introduce additional errors. Other than studies by FAP-24 in the 1990s, there has been very little published information on these estimates.

Table 1 summarizes estimates of annual suspended load from different time periods on the Jamuna and Ganges Rivers.

Table 1: Total suspended sediment load in the Jamuna and Ganges Rivers.

Source	Period of Sediment Record	Suspended Sediment (10^6 t /yr)	
		Jamuna	Ganges
Coleman (1969)	1958-1962	610	480
BWDB (1972) quoted in CBJET (1991)	1966-1969	553	494
Delft Hydraulics/DHI (1996c)	1993-1996	402	632
Rahman et al. (2018)	1958-2001/8*	220 (for 2015)	250 (for 2015)

* Jamuna data until 2001 and Ganges data until 2008 were used, due to doubtful quality of later data

The annual suspended sediment supply to the Jamuna River is reported to be in the order of 400 to 600 million tons per year (BWDB, 1972; Delft Hydraulics and DHI, 1996; Islam et al., 1999; Rahman et al., 2018). The suspended load includes suspended sand (which is often considered equivalent to the bed material load) as well as fine silt and clay, which are often considered as wash load. Previous studies report the bed material load ranges between 10% and 30% of the total sediment load (Best et al., 2007). It is the bed material load that forms most of the active channel bars and riverbed sediments. The finer wash load is flushed through the channel to the delta or is deposited overbank on the floodplain.

The Ganges River transports in the order of 300 to 600 million tons of suspended sediment per year to its confluence with the Jamuna River (Coleman, 1969; BWDB, 1972 quoted in CBJET (1991); Hossain, 1992; Delft Hydraulics and DHI, 1996; Islam et al., 1999).

The sediment gauging stations on both the Jamuna and Ganges Rivers are approximately 150 km upstream of their confluence, and a substantial amount of sediment may be sequestered onto their floodplains (Goodbred and Kuehl, 1998). The measured suspended load in the Padma River is less than the sum of transport in the Ganges and Jamuna Rivers; estimates on the Padma River range from 755 to 948 million tons per year. This factor limits the accuracy of developing quantitative sediment budgets within individual channel reaches.

Several studies (CEGIS, 2012; Rahman et al., 2018) suggest the annual load of the Ganges and Jamuna Rivers have decreased over the last 30 years. However, the uncertain and varying quality of the data over time makes it difficult to draw firm conclusions. An upgraded sediment monitoring network is needed to resolve these issues and to improve confidence in predicting future channel behavior.

6.2 Water Inflows

Rainfall during the summer monsoon is the main source of flow in the Brahmaputra River system, although there is some smaller coincident contribution from snowmelt in the Himalayas. Monsoon precipitation typically begins over the Brahmaputra Basin earlier than the Ganges, and so flow in the Jamuna River typically peaks in July and in the Ganges River in late August. Figure 5 presents the mean daily flow of the Jamuna and Ganges Rivers at Bahadurabad for the Jamuna River and at Hardinge Bridge for the Ganges River. However, the Jamuna River can have a second or delayed flow peak coincident with that of the Ganges River. The Jamuna River begins to rise in March to April as a result of heavy pre-monsoon rainfall in northeast India and northeast Bangladesh. The Ganges River starts to rise later in May as pre-monsoon rains start later in that catchment. Both rivers rise rapidly with the onset of monsoon rainfall in June. Flow rates in both rivers generally start to decrease rapidly from the end of September through November, then continue to recede into the dry season. The Jamuna River typically reaches its lowest flow of about 8,000 m^3/s in February and the Ganges River reaches its minimum flow of about 650 m^3/s in between March and May.

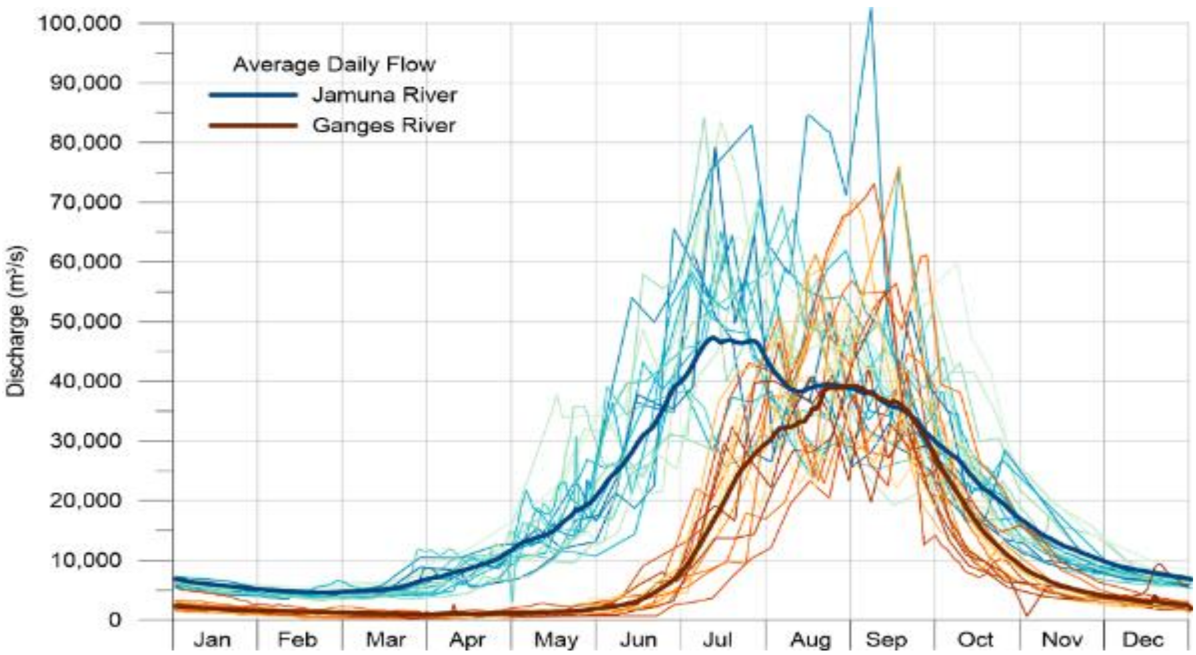

Figure 5: Mean daily flow of Jamuna and Ganges Rivers. Bold lines are the pre-2012 average of available records. Fine lines are selected individual years (data BWDB).

Flood peaks on the Jamuna River increase from about 66,000 m^3/s for a 2-year recurrence interval event to about 109,000 m^3/s for a 100-year recurrence interval event. Flood peaks on the Ganges River are lower, increasing from about 49,000 m^3/s for a 2-year recurrence interval event to about 78,000 m^3/s for a 100-year recurrence interval event. The Padma River combines flow from both the Jamuna and Ganges Rivers, but because their peak flows are typically offset, its peak flows are substantially less than the sum of the peaks for those two tributaries. These increase from 94,000 m^3/s for a 2-year recurrence interval event to 152,000 m^3/s for a 100-year recurrence interval event. The intensity of monsoonal precipitation varies on a decadal timescale, leading to alternating periods of higher than normal flood flows and lower than normal flood flows (Chowdhury and Ward, 2004; Fichtner and NHC, 2015). In the Brahmaputra Basin, the periods from 1900 to 1910, 1926 to 1948, and 1980 to 1998 included above-average monsoon-season rainfall, while the periods from 1949 through 1972 and from 2001 through 2010 included below average monsoon-season rainfall. The annual sediment loads are expected to be affected by these cyclical climatic-hydrological variations.

6.3 The River System

The river responds to variability in the incoming flux of water and sediment by changing its channel morphology. In many areas, the riverbanks are composed of recently deposited alluvium that is indistinguishable from sediment within the active channel, but in others, bank materials consist of stronger cohesive materials that are more resistant to erosion or are protected from erosion by manmade structures. In areas with an alluvial boundary, the channel morphology is more responsive to variability in the incoming fluxes than in areas where the banks are less free to erode. These factors, along with the distinct change in discharge that occurs at the confluence of the Ganges and Jamuna Rivers give rise to distinct reaches of the river with differing morphological characteristics.

Figure 1 shows the Jamuna and Padma Rivers sub-divided into five sub-reaches and three transitional reaches for the purposes of the RSP. The ends of each reach are defined by the most significant shifts in hydraulic and morphological characteristics.

Entrance Reach: This reach is defined by the change of direction of the Jamuna River at the Bangladesh-India border where the flow moves from a westward to a southward bearing. The irregular line of the India-Bangladesh border bisects this curve. The reach ends where the Jamuna River has both its banks in Bangladesh, just south of the Dharla River on the right bank and with the beginning of the Sherpur District in the left bank. Kurigram District is located on its left bank. The right bank of the Jamuna River is embanked from the Dharla River to the Teesta River. This embankment forms part of the Kurigram Irrigation Project.

Reach 1: About 90 km in length, this reach extends from about 25 km upstream of where the Teesta River meets the Jamuna River to Sariakandi in Bogra District, where the Jamuna and the Bangali Rivers are only few hundred meters apart. This reach is characterized as the most unstable part of the Jamuna River with a high braiding index and frequent channel changes. The Brahmaputra Right Embankment begins at the Teesta River and extends into Reach 3. There is no systematic embankment on the left bank. The offtake of the Old Brahmaputra River is located about halfway down this reach on the left bank. With limited riverbank protection works, both banks are mostly in a natural condition and subject to annually changing erosion and accretion patterns.

Reach 2: This reach is about 60 km in length and extends to the Bangabandhu Bridge. Over the past three decades the Jamuna River has developed a narrow corridor and flows mostly as one main single channel at the Sariakandi transition into Reach 2. This single channel widens into an unstable main corridor that flows predominantly along the right bank since the 1990s. The main channel that flowed along the left bank until the mid-1980s has reduced to a flood spill channel flowing through loose recent deposits. Due to the soft boundaries, this spill channel still exhibits substantial erosion potential during high floods. Between both channels there is a very large developed char. Historically, the Brahmaputra Right Embankment has been eroded frequently in this reach. Today, along 70% of the right bank of this reach the embankment line is reasonably well protected with long-guiding revetments and as a result the floodplain behind the embankment receives little river flooding. There is only a short stretch of embankment along the left bank of the river close to the Bangabandhu Bridge.

Reach 3: This reach is about 60 km in length and extends from the Bangabandhu Bridge to about 10 km upstream of the confluence of the Jamuna and Ganges Rivers at the east-west interconnector. The guide bunds for the Bangabandhu Bridge have reduced the river width to 5 km and this has created a single, straight channel that continues for the next 20 km. At Enayetpur the single channel bifurcates into two main channels, each flowing along opposite banks until they reach the confluence with the Ganges River. In 2012, pilot dredging initiated a destabilizing process of this reach and without counter measures this process will likely result in significant morphological changes. The Hurashagar River enters the Jamuna River on its right bank at approximately the midpoint of this reach and this is also the end of the Brahmaputra Right Embankment. The lower half of the right bank of this reach is protected against river flooding through the embankment of the Pabna Irrigation and Rural Development Project. This embankment continues along the Ganges River left bank at the confluence. Within this reach, nearly half of the right bank is protected against riverbank erosion. On the left bank, revetment work has been built at only two locations. The Dhaleswari River System originates from three locations at the left bank of the Jamuna River and supplies water to the southern part of the North-central Zone, including Dhaka.

Jamuna-Ganges Confluence: This reach extends about 10 km into the three rivers forming it: the Ganges joins from the west, the Jamuna from the north, and the combined flow of the Padma River leaves the confluence in a southeast direction. The morphology in this area remains variable due to the annually changing flow and sediment composition of the Jamuna and Ganges Rivers, each of which can exhibit quite different flood characteristics. Over the last half century, the width of the Jamuna River increased and the confluence shifted about 10 km to the east and south. As a consequence, a large triangular-shaped char formed and is bordered by the Ganges River left bank and the Jamuna River right bank channel as it turns southeast towards the confluence. The Padma River starts with a deep scour resulting from the confluence of the two powerful upstream rivers.

Reach 4: This is the first reach in the Padma River and is about 60 km in length. This reach extends from just below the confluence of the Ganges and Jamuna Rivers to the Padma Bridge, where the width of the river is reduced to about 5 km. The upper half of this reach switches between a single and a two-channel (anabranched) planform. Over the last two decades a single channel along the left bank has been dominant while a declining flood spill channel flows along the right bank. The pattern in the downstream half of the reach switches from a straight channel along the left bank to a meandering channel, deeply entering into the south bank. Because the meander is evolving it is probable that the Padma River adjusts to a straight course over the next five years. Much of the left bank consists of erosion-resistant material. The only area of recent (loose) deposits on the left bank are at Harirampur. Around 2015 this area was protected from erosion with a 9 km long revetment. On the right bank, around the same length of riverbank protection was constructed in the early

2000s to reduce erosion around the town of Faridpur. Some other riverbank protection works are located on the Ganges River right bank at Rajbari, at two locations on the left bank, and at the Padma Bridge to guide a meandering channel through the bridge opening. There are no major flood embankments along either side of the river.

Reach 5: This reach is about 30 km in length and extends from the Padma Bridge to the Padma/Meghna confluence. Here the Padma River also exhibits an alternating channel pattern. The channel pattern comprises either a straight channel with flow directed towards Chandpur or two separate channels separated by a large char. These two channels in turn each have formed their own confluence with the incoming Meghna River. Presently, there is a single channel planform, which might change when the upstream reach reverts to a straight channel in future. There is limited riverbank protection on the left bank, though on the right bank about 10 km of protection is provided at Naria, upstream of the naturally erosion-resistant area at Shariatpur. This reach has no major flood embankments.

Meghna-Padma Confluence: This reach is about 20 km in length (from north to south) and extends from the Upper Meghna at the Meghna-Dhonagoda Irrigation Project to the Lower Meghna at Chandpur Town. The stability of the confluence is primarily ensured by erosion and flood protection provided to Chandpur Town on the left bank of the river. Additional stability is provided by the Meghna-Dhonagoda Irrigation Project, where the left bank is protected with nearly 5 km of revetment, and the irrigation project is fully embanked.

6.4 Channel Instability and Widening

The relative stability of the channel tends to increase from upstream to downstream as the sediment concentration (ratio of sediment flux to water flux) and bed material grainsize decrease and as the proportion of the channel banks interacting with cohesive sediment and bank protection structures increases. The Padma River is generally more stable than the Jamuna River, and the lower reach (Reach 3) of the Jamuna is more stable than the upstream reaches. The reach of the Jamuna River at the Indian Border is the least stable.

The active widths of the Jamuna and Padma Rivers have undergone significant changes over time, resulting in severe erosion, damage to flood embankments, and flooding problems along the rivers. Figure 6 shows the planform of the river in 1943, 1976, 1996, 2001 and 2018. The Jamuna River was at its narrowest in the early 1970s. At this period, the channel was much narrower than it had been three decades earlier, with a median active width of only 4.9 km and channel belt width of 7.9 km. From the 1970s through 2000, the channel continued to widen; however, the active channel width in the 2000s only slightly exceeded that observed in 1943. The width has remained virtually constant since 2000.

The overall trend has been erosion along the right (western) bank and accretion along the left bank. The erosion along the right bank has slowed recently, partly due to the construction of bank protection works since the mid 1990s. Due to the dramatic widening of the Jamuna River, superimposed on a natural shift in western direction, it has been necessary to retire the embankments along right bank which were constructed in the 1960s.

Erosion along Padma River is dominated by the bank erosion along curved anabranches. Erosion also takes place along more cohesive banks but at a much slower scale. Overall accretion along the

Padma River is negligible. The increase in total width is less pronounced on the Padma than on the Jamuna River.

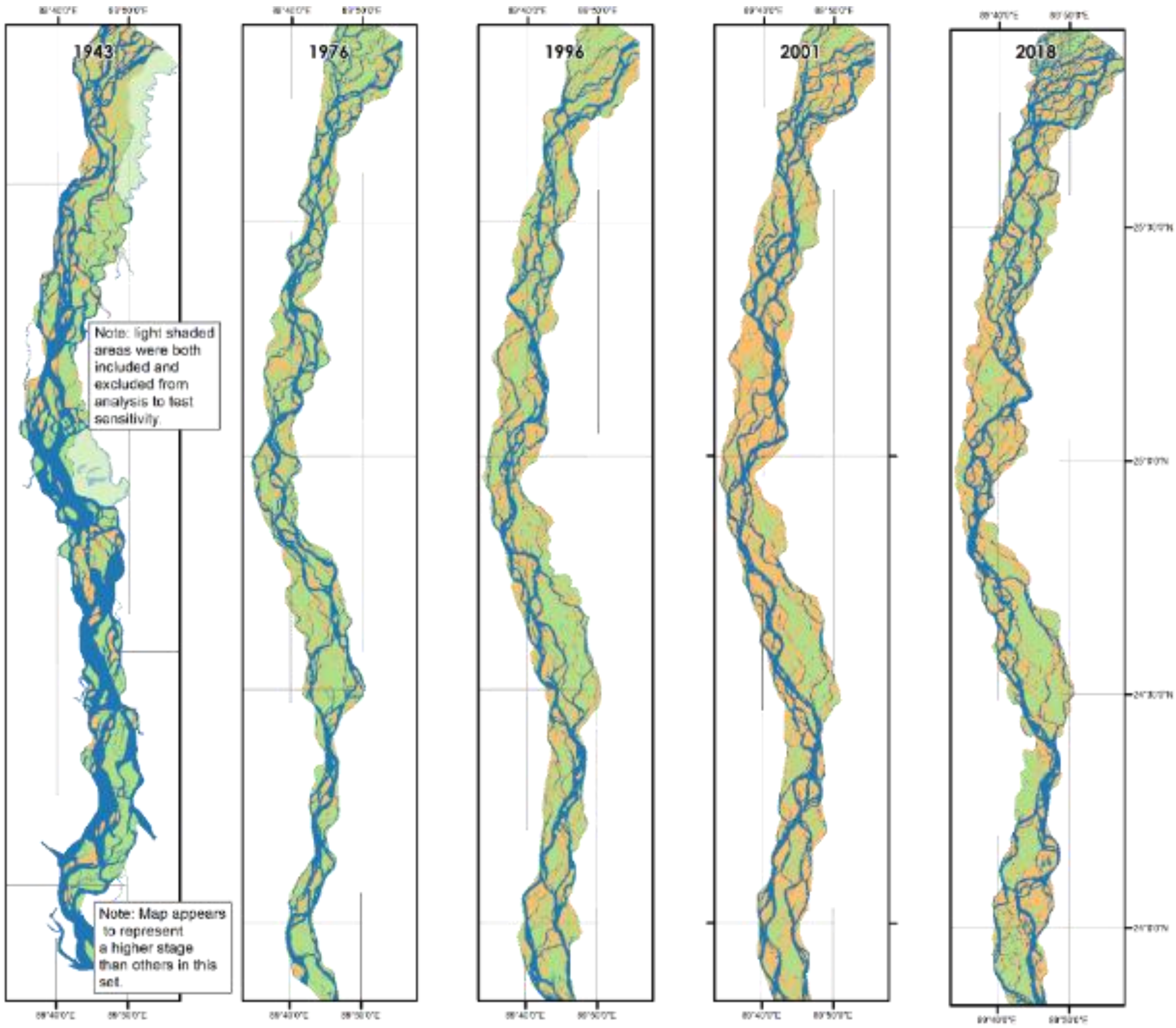

Figure 6: Channel pattern, Jamuna River 1943 to 2018 (ISPMC).

The observed instability of the Jamuna and Padma Rivers emphasizes that they are dynamic landforms, which, like most rivers, adjust to variability in the incoming flux of water and sediment by changing the channel morphology (Church, 2006). Explanations for the dramatic widening of the Jamuna River in the 1980s and 1990s have focused on the potential impacts of a sediment wave resulting from the 1950 Great Assam Earthquake (Goswami, 1985; Delft Hydraulics and DHI, 1996; Sarker and Thorne, 2006; Sarker, 2008) and effects of numerous large floods during that period (Deka et al., 2013; Fichtner and NHC, 2015). Likely both of these forcing mechanisms have affected the channel morphology (Figure 7). Future perturbations in both sediment supply and discharge are expected in response to land use change, climate change and variability, and earthquakes. An erodible corridor around the channel should be maintained to allow for channel adjustment to these expected future perturbations.

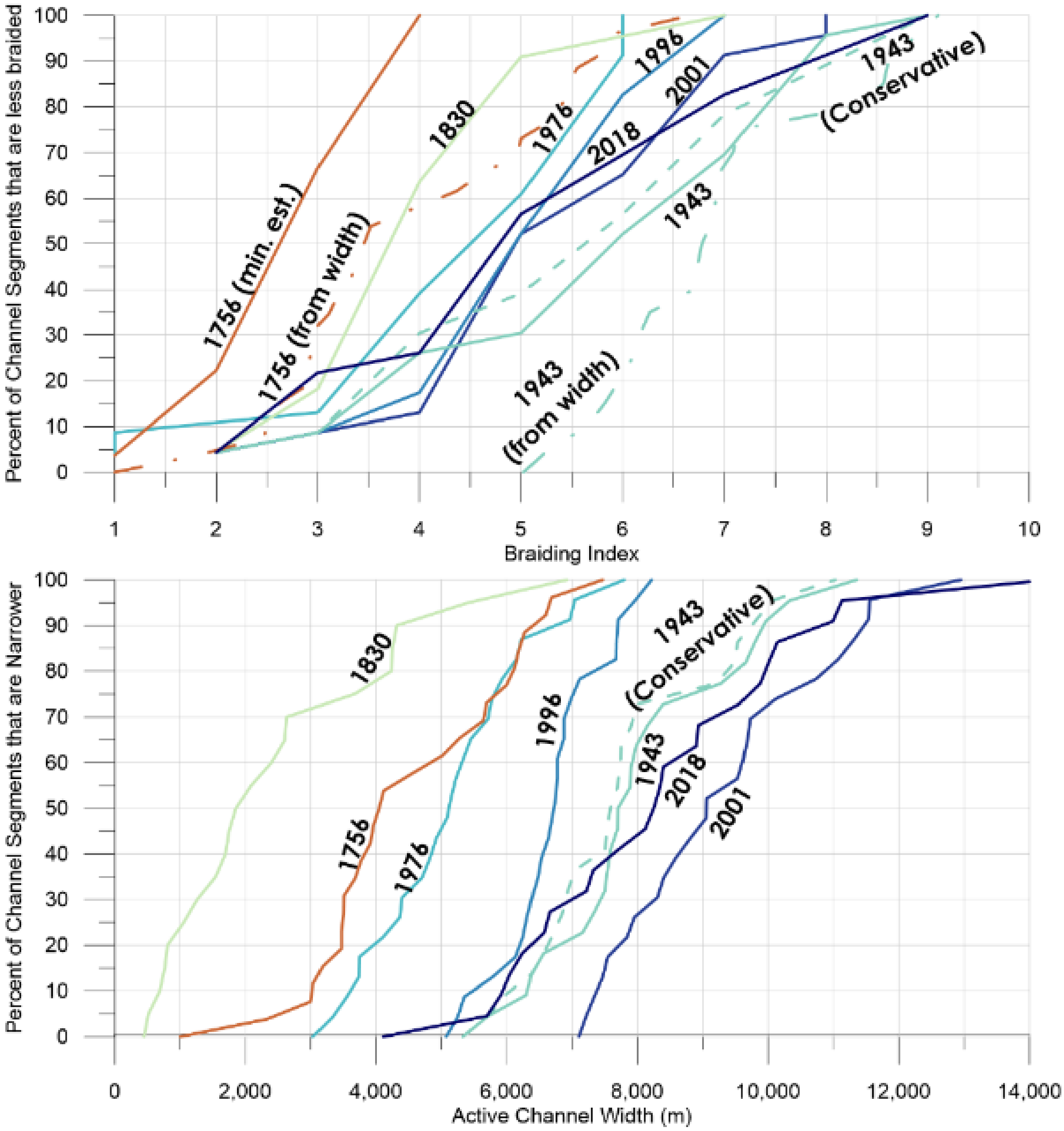

Figure 7: Cumulative distribution plots of braiding intensity (top) and channel width (bottom) of the Jamuna River within Bangladesh (ISPMC).

7 WHY BANK EROSION MATTERS

7.1 Erosion and Flood Damages on Main Rivers

Bank erosion and channel widening are a significant constraint to development, due to the loss of agricultural land, erosion and breaching of flood embankments, and destruction of infrastructure. Erosion of flood embankments means the structures do not achieve flood protection benefits. Often embankments fail at water levels well below their design capacity due to bank erosion and scour, resulting in wide-spread flooding. Bangladesh's high population density, combined with the fact that most of Bangladesh is flood prone, prevents the country from restricting settlement in high-risk areas. As a result, the poor are left to settle in the highest risk areas on the floodplain, as no other land is available. As a consequence, the flood risk has continually increased which is reflected in the increasing cost to mitigate flood disasters.

The occurrence of embankment failures and relocations (termed "retirements") along the right bank of the Jamuna River have been documented by CEGIS (Fichtner and NHC, 2015). Figure 8 summarizes the frequency of embankment failures and retirements due to erosion along the right bank of the Jamuna River during the period 1968 to 2013. As a result, the population on the floodplain has lost approximately 1,000 km^2 of land along the Jamuna River.

7.2 Impacts to Distributary Channels

Channel instability and bank erosion on the main rivers contribute to problems of impaired water supply, water quality, and inland transportation on the large distributary branches, including the Old Brahmaputra, Dhaleshwari and Arial Khan Rivers. Examples of ongoing problems are briefly summarized here.

- The Old Brahmaputra River is the relict of the Brahmaputra River before it avulsed to the present Jamuna River in decades around 1800. It only retains a connection to the Brahmaputra-Jamuna at high floods and its flows are still declining. The location of the offtake shifted 15 km between 1973 and 2010.
- The Dhaleshwari River is a distributary of the Jamuna River and has experienced a serious decline in flows as a result of channel sedimentation. It has several parallel offtakes and over time each of these offtakes has shifted its location over several kilometers.
- The Arial Khan River was the main course of the Padma River in 1776. Presently, it is a right bank distributary of the Padma. The flows in the Arial Khan have been declining since the 1980s as a result of planform changes on the Padma. The Arial Khan had several parallel active offtakes in the past, but presently only a single offtake at Chowdhury Char is active.

Bank erosion and channel instability on the main rivers can result in smaller distributary channels being abandoned due to unfavorable morphodynamic changes near their offtakes. Consequently, localized instability near the offtake can result in impacts over much larger spatial areas, far away from the source of the problem. This jeopardizes and constrains water supply, water quality, and navigation along the abandoned distributary rivers.

7.3 Impacts to Navigation

Channel shifting and widening results in a shallower, unstable navigation channel during the dry season, restricting expansion of inland navigation and requiring high rates of maintenance dredging.

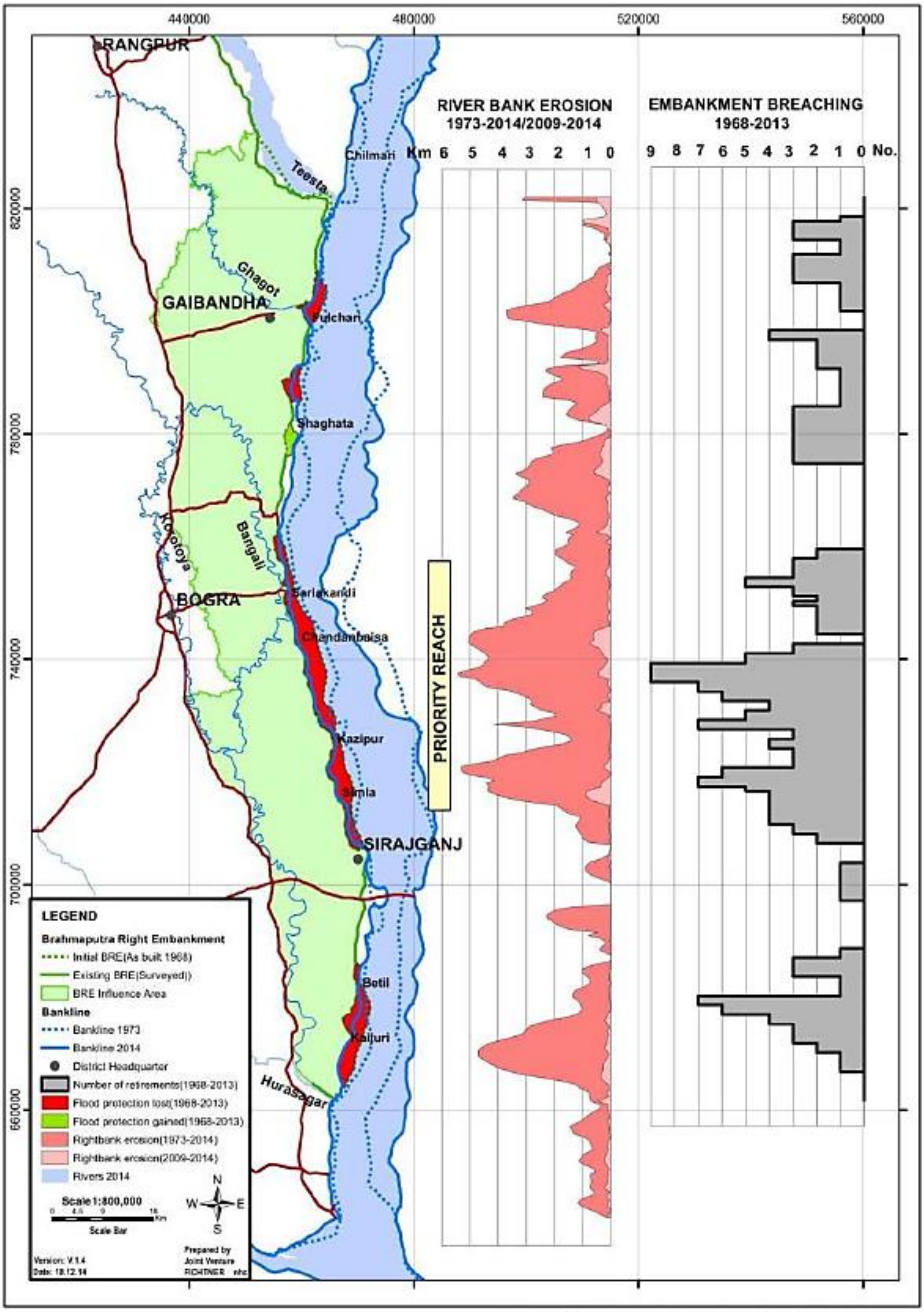

Figure 8: Erosion rates and embankment relocations, Brahmaputra Right Embankment (RBIP, 2015).

7.4 Summary

Past bank erosion and channel instability have contributed significantly to a range of river management problems in the region. Developing a more stable river corridor should contribute to improving three main issues:

- Improving the reliability of flood protection embankments.
- Improving water supply and water quality along major distributary channels to the surrounding region.
- Improving inland water transportation both in the main rivers and distributary channels.

7.5 Future Conditions

An important finding from the geomorphic studies is that the river in the early 21st century is the widest at any point in the historical record (Figure 9), regardless of the morphodynamic mechanism driving these changes. Between 1980 and 2000 the river widened very fast. Over the last decade a small reduction in width has been observed, indicating a period of settlement. Taken together, these observations of highly variable and rapidly changing river planform clearly show that there is a wide range of plausible “regime” widths for the river in the future. The width appears to sensitively integrate effects of variable flood discharge, sediment supply, and bank strength. These factors are termed “hydro-geomorphic controls” in this report and are used to represent future scenarios that will drive the pattern of instability along the rivers. Of these, future changes to sediment inflow will be one of the most important factors in governing the stability of the river.

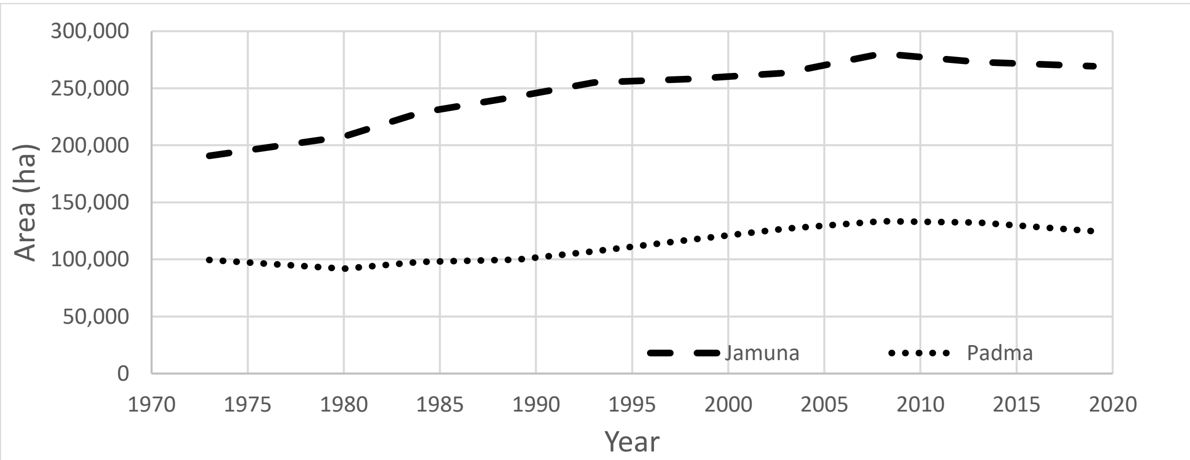

Figure 9: Total channel area of Jamuna and Padma rivers from the mid-1970s to 2019 (ISPMC).

Associated with the future “regime” width is the associated stable channel pattern that can develop under these future hydro-geomorphic controls. Ideally, future river stabilization measures such as river training should be compatible with the river’s morphological characteristics. This requires understanding the formative processes that control bar formation, channel sinuosity, and channel pattern type. Many empirical and theoretical studies have been carried out to predict channel patterns (Parker, 1976; Ferguson, 1987; Crosato and Mosselman, 2009). A recent review paper examined both empirical and theoretical methods and concluded formative conditions of these different channel patterns are not well understood and cannot yet be predicted well, neither by classical empirical nor by theoretical methods (Kleinhans et al., 2011). In spite of these limitations, there is a relatively good conceptual understanding of the relationship between channel pattern, channel sediment characteristics and sediment inflows. Figure 10 illustrates a conceptual model of channel pattern response to sediment inflows for a sand-bed river (Church, 2006).

Unfortunately, the available sediment data is inadequate to make reliable assessments about recent trends. A significant increase in monitoring effort would be required to reliably assess annual sediment loads on the main rivers and to develop sediment budgets. Until this occurs, trends in sediment loads can only be described conceptually. In a later section of this report, the effects of three plausible future scenarios on river stabilization actions are discussed:

- **Scenario 1**: Annual sediment inflows continue to slowly decrease asymptotically, approaching a steady-state.
- **Scenario 2:** Annual sediment inflows remain approximately constant over time, increasing and decreasing from year to year in response to annual flood events.
- **Scenario 3:** Annual sediment inflows increase over the next few decades then gradually decline again (a new sediment wave).

It is expected that the planform of the river would respond to each of these trends in general accordance with Figure 10. Scenario 1 is believed to have occurred over the last few decades (Rahman et al., 2018; CEGIS, 2012). An increase in sediment inflows (Scenario 3) is a plausible response to periodic decadal trends in runoff and sediment yield in the headwaters, or as a result of longer-term effects due to climate change, land use impacts, landslides, or tectonics. This trend could potentially reactivate channel instability and widening processes. It could make it more difficult to narrow and permanently change the planform from braided to meandering. It would also

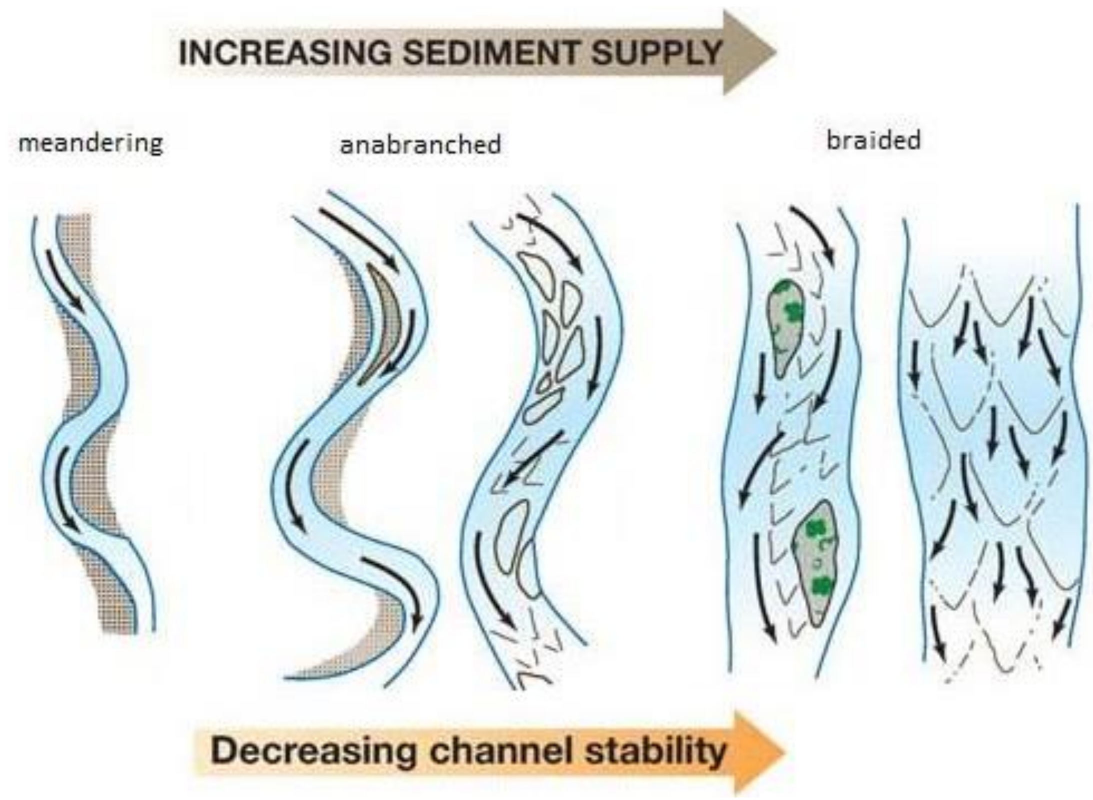

Figure 10: Sediment supply control of river channel stability, unregulated alluvial sand-bed channel. Simplified illustration (modified from Church, 2006).

increase requirement for maintenance of bank protection structures, embankments and navigation channels.

Monitoring ongoing channel bank line and channel pattern changes using satellite imagery is already well established. Improving the reliability of sediment monitoring networks on the river system will be a priority for long-term planning and design of the RSP. However, improved sediment measurement going forward does not eliminate the data gap over the last 30 years when the river morphology was undergoing significant change. In addition, more systematic stabilization efforts have been undertaken since the mid-2000s. These factors will make it difficult to distinguish natural trends in river morphology from the effects of river stabilization works.

PART THREE – GOALS, OBJECTIVES, PERFORMANCE INDICATORS, AND UNCERTAINTIES

This section provides a brief overview of the goals and objectives of the plan. More detailed discussion is contained in the Strategic framework for river stabilization and development: Jamuna-Padma and dependent areas (Supplementary Annex A1).

8 GOALS

The Bangladesh Delta Plan 2100 (GED, 2018) states that many of the water-related challenges in the country relate to the major rivers and that these have national importance since they are the backbone of the delta system. A subset of the strategies for dealing with the major rivers as presented by this Delta Plan has become the goal for this RSP:

1. Provide adequate room for the river and infrastructure to reduce flood risks;
2. Improve the conveyance capacity as well as stabilize the rivers;
3. Provide fresh water of sufficient quantity and quality, particularly through the improvement of distributaries;
4. Maintain ecological balance and values (assets) of the rivers;
5. Promote safe and reliable waterway transport in the river system;
6. Develop a strategy for sediment management adopting natural processes as well as dredging and char land development; and
7. Strengthen river and estuary management in the newly accreted lands and land use planning.

9 OBJECTIVES AND PERFOMANCE INDICATORS

The following four objectives have been developed to meet the overall project goals:

1. A stabilized planform;
2. Land recovery in a narrowed corridor;
3. Provision of stable offtake locations; and
4. A more stable and deeper dry season navigation channel.

1. The success of the project in meeting these objectives will be assessed using a number of performance indicators, as described below in Trends in past sediment inflows are very uncertain and it is not clear whether the future conditions will be similar to the recent past. Cyclical patterns of runoff and sediment yield could complicate future conditions. The occurrence of another major earthquake should be anticipated and accounted for in the plan.
2. Land use changes and large-scale water resource projects in the headwaters (dams, water diversions, river channelization) could substantially alter the magnitude and timing of sediment-water inflows from the Jamuna and Ganges Rivers.

3. Impacts of climate change and sea level rise are expected to result in more severe flood conditions throughout many parts of the region. The impact of these changes on sediment production in the headwaters and on channel stability along the main rivers is unknown.
4. Future navigation channel usage and channel requirements (depths and width).
5. Water demand and water quality requirements in the main distributary rivers.
6. Uncertainties related to project design and prediction of channel response.

9.1.1 Data Limitations

There is good historical information available to assess planform changes on the rivers and CEGIS has a high level of expertise in using this data to make short term predictions of channel changes. However, information on vertical changes in the channels and on floodplains is much more limited.

Table 2.

10 UNCERTAINTIES

It is important to identify the types of uncertainties that will affect future trends and driving forces that affect the region and may influence the performance of future actions.

10.1 Uncertainties Related to Future Conditions

The technical studies summarized in the Supplementary Annexes include descriptions of the major uncertainties associated with future climatic, hydrological, morphological and socio-economic conditions that affect the region. The following points highlight these issues.

7. Trends in past sediment inflows are very uncertain and it is not clear whether the future conditions will be similar to the recent past. Cyclical patterns of runoff and sediment yield could complicate future conditions. The occurrence of another major earthquake should be anticipated and accounted for in the plan.
8. Land use changes and large-scale water resource projects in the headwaters (dams, water diversions, river channelization) could substantially alter the magnitude and timing of sediment-water inflows from the Jamuna and Ganges Rivers.
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10. Future navigation channel usage and channel requirements (depths and width).
11. Water demand and water quality requirements in the main distributary rivers.
12. Uncertainties related to project design and prediction of channel response.

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There is good historical information available to assess planform changes on the rivers and CEGIS has a high level of expertise in using this data to make short term predictions of channel changes. However, information on vertical changes in the channels and on floodplains is much more limited.

Table 2: Performance indicators for meeting the objectives of the RSP.

Objective	Description	Performance Indicator
Stabilized planform	Channels shift within a defined alluvial corridor. Planform is mainly anabranched or meandering with defined low-flow channels.	1. Reduced occurrence of embankment breaching 2. Reduced loss of agricultural land by erosion 3. Reduced emergency bank protection repairs and reduced maintenance costs 4. Minimal negative impacts upstream and downstream of project 5. Increased number of protected habitats
Land recovery and narrowed corridor	Recovery of floodplain land previously eroded by the river	1. Increase in usable land area 2. Increased economic activities 3. Socio-economic indicators
Providing stable offtake locations	Offtakes located in stable locations and connected to main rivers during the dry season.	1. Reliable water supply and navigation 2. Reduction in maintenance dredging 3. Improvement of water quality and groundwater levels 4. Improvement of wetlands
More stable and deeper dry season navigation channel	Availability of year-round navigable channel	1. Channels passable by design vessel all year 2. Maintenance dredging reduced over time

The reliability of sediment load data, and the size distribution of the sediment loads varies considerably over time. The accuracy of annual sediment loads in many years is expected to be very low. Efforts to identify trends over time or to develop sediment budgets by comparing sediment loads at two stations are virtually meaningless if the accuracy of the estimates is low. Reliable estimates of sediment and water inflows will be needed to monitor conditions during the implementation of the plan. Unfortunately, even if improvements are made to the data collection, there may be no comparable, reliable baseline data to compare these values to.

10.1.2 Uncertainties in Stabilized Channel Design

Transforming the river's planform (for example, converting a braided channel to a meandering pattern) and creating a dynamically stable alluvial channel will be an unprecedented engineering challenge. Given that the Jamuna River is the largest braided sand-bed river in the word, most experience on smaller, less morphologically active rivers is not transferrable to the situation in Bangladesh. No other river has a comparable set of physiographic, geologic and hydrological parameters. Consequently, pilot testing of concepts and "learning by doing" will be critically important steps in developing and verifying stabilization concepts and designs. For example, one objective of the Plan is to promote reclamation of former floodplain land that has been lost to the river due to bank erosion. It is not possible to make reliable predictions about the rate of vertical accretion and spatial extent of new land formation at the present time. The actual amount of land reclamation that may be realistically achieved over a relatively short period of time (less than 10 years) is uncertain.

10.1.3 Uncertainties in Impact Prediction

Factors contributing to uncertainties in impact prediction include:

- **Inherent unpredictability of some physical processes, and interactions among them and with RSP impacts:** Evolution of RSP main river channels is inherently unpredictable (even with "perfect" data and models). In turn, channel evolution can affect distributary flows; if a channel degrades at a distributary offtake, distributary low season flows can be reduced or eliminated. This introduces uncertainty into prediction of the impacts of physical works constructed upstream and downstream of such offtakes.

- **Data limitations**: Gaps in historical and real-time information on flows, sediment, channel cross-sections, and upstream meteorology and land use constrain predictive efforts.
- **Factors external to the RSP**: As the future environment of the project is uncertain, so the environment-on-project impacts are uncertain. For example, future climate characteristics affecting the RSP area are uncertain. Future levels of institutional and social support (or lack thereof) to implement the RSP are also uncertain. Future earthquakes, affecting the RSP area directly and in its upstream catchment, are expected to be similar to the pattern of past such events, but their future timing, location, magnitude, and impacts cannot be predicted.
- **Adaptive nature of the RSP:** Impact prediction of the RSP at this stage is limited to identifying non-site-specific impacts that could be caused by each of the generic infrastructure types (geobag revetments, embankments, dredging, etc.) constructed at a generic infrastructure site for that type. Physical interventions proposed by the RSP are currently specified as to type only. Under the RSP adaptive approach, their specific design parameters (number, site, dimensions, scheduling, engineering and construction details) will be determined as deemed appropriate over time.

PART FOUR – REVIEW OF RIVER STABILIZATION EXPERIENCE

11 INTERNATIONAL RIVER STABILIZATION EXPERIENCE

Experience from other large rivers outside of Bangladesh was reviewed by FRERMIP. Unfortunately, there are few rivers in the world comparable to the Jamuna/Padma River systems due to the large sediment load and discharge, the fine-grained nature of the river's bed and banks, its unique tectonic setting, and its wide, unconfined floodplain (Supplementary Annex D2). The Yellow River in China, with its extremely high sediment load and history of extreme channel shifting was identified as the most comparable to rivers in Bangladesh, although the Yellow River has never been used or trained for navigation.

Long-term efforts to stabilize the Yellow River were recently reviewed by Wang and Liu (2019). The study compared the effectiveness of river stabilization measures over a time period spanning 2,000 years. Two different strategies were defined: the "narrow river and scouring sediment" strategy and the "wide river and depositing sediment" strategy. The former approach involved narrowing the river and confining the flood within the mainstem channel in order to raise the velocity and keep the sediment carrying capacity high, preventing sediment depositing and even promoting bed scouring. The latter approach involved building enhanced levees set tens of kilometers apart, giving enough space for sediment deposition and diverting water and sediment into diversion basins to attenuate the effects of floods. It was concluded: "*the narrow river and scouring sediment strategy has only a short-term effect of levee breach control and flood mitigation. The wide river and depositing sediment strategy can essentially mitigate flood disasters and reduce levee breaches for a long period of time*".

The adopted strategy of the Yellow River Conservancy Commission (YRCC) is essentially based on the wide river concept and involves a combination of measures including reducing the flood discharge (and sediment loads) with reservoirs, enhancing the capacity of the river channel by enhancing and reinforcing the levees, and retaining floodwater in detention basins connected laterally to the floodplains.

Figure 11 illustrates an example of river stabilization on the Yellow River.

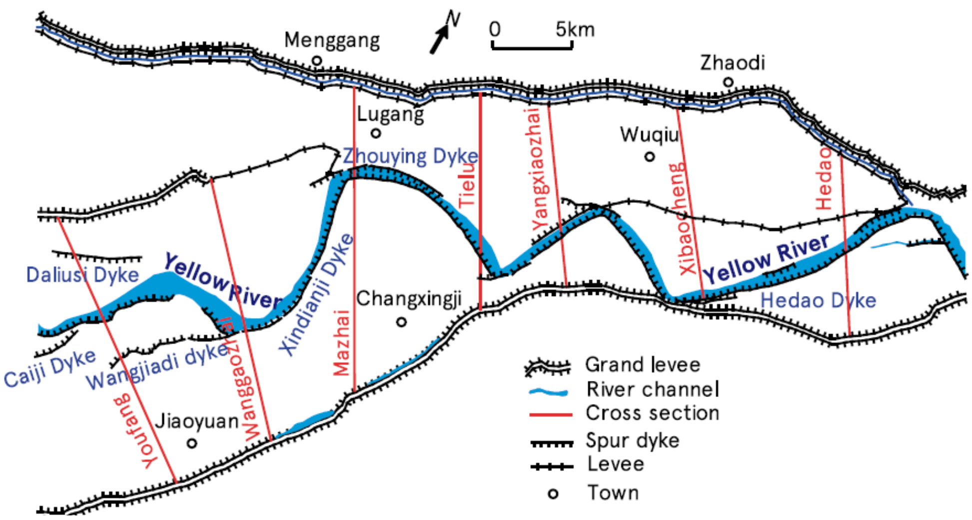


Figure 11: Wide river valley example – Grand Levees, Henan Province (Wang and Liu, 2019).

A wide range of specific river training measures have been used to control the lateral movement of the river channel within the stabilized corridor. The method of bend control has been adopted at many sites and is characterized by concentrating the river flow into a mostly single channel and guiding the course of the river with successive protected bends with opposite curvatures, as illustrated in Figure 12. A similar approach was proposed in CBJET (1991) for the Jamuna River (described further in Section 12). However, information on the performance of these measures on braided channels subject to high sediment loads is still very limited. Design methods for estimating stable channel parameters and assessing channel response are also limited. Examples of research and progress in this field are the work by Mosselman et al. (2000) and Wu et al. (2005).

River stabilization in China has been accompanied by large-scale sediment control programs in the headwaters, as well as upstream flow regulation and water diversion (Wang and Liu, 2019; Yu et al., 2011; Wang et al., 2007; Best, 2019). As a result, the sediment load on the Yellow River has decreased dramatically over the last 50 years (Figure 13). Although the stability of the river has been enhanced, the reduction in sediment loads has resulted in the Yellow River delta to stop creating new land and the coastline is reported to be retreating.

Past experience on the Yellow River and other rivers such as the Mississippi River and Rhine River has shown that comprehensive stabilization projects require substantial pilot-scale trials, as well as updating of plan strategies and scheme designs in response to observed response of the rivers. Sustained effort over several decades may be required. This time frame is expected to apply to this Plan as well.

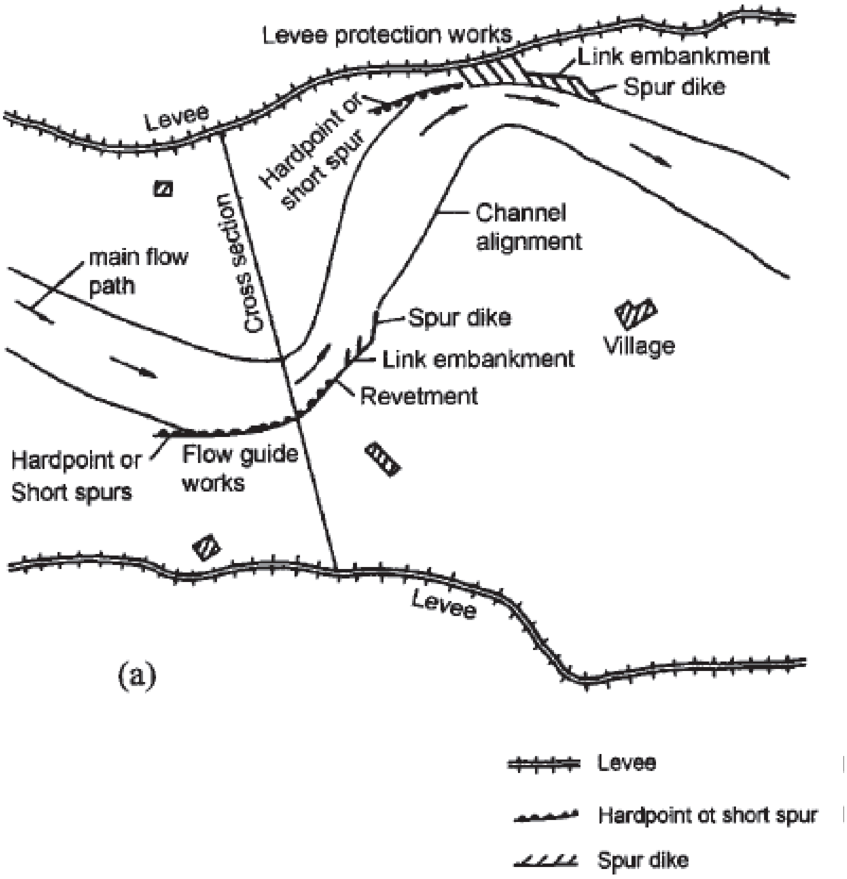


Figure 12: Bend control example, Yellow River (Wu et al., 2005).

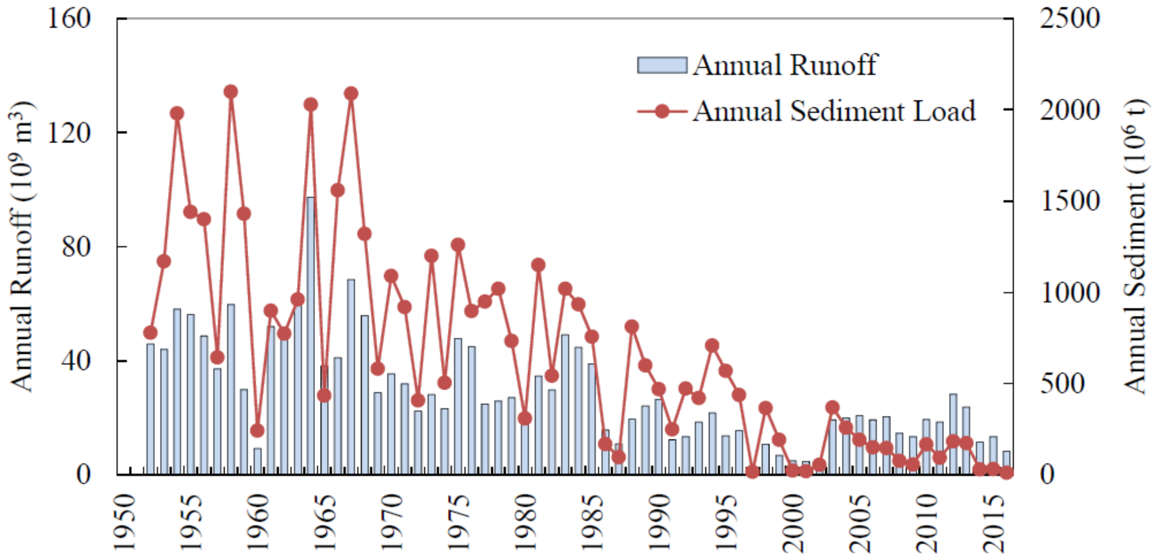


Figure 13: Water and sediment load, Lower Yellow River, Lijin Station 1950 -2016 (Wang and Liu, 2019).

12 BANGLADESH RIVER STABILIZATION EXPERIENCE

Modern riverbank protection in Bangladesh emerged through a process of "learning by doing" dating back to early activities in the 1960s. Most of the previous river stabilization work has been reactive in nature, with projects focused at protecting high-value sites such as towns or flood control projects. Past examples include Rajshahi on the Ganges River, Sirajganj on the Jamuna River, and Chandpur at the transition to the Lower Meghna River. Protective works were never fully completed and consisted of a continued effort of construction and reconstruction, applying different methods and technologies, often on emergency basis. This period is characterized by "fire fighting" the rapid widening of the Brahmaputra System, resource and fund constraints, and a lack of understanding of the governing river processes. Most studies and research focused on design issues related to performance of specific structures (groynes versus revetments) or materials (concrete blocks versus geobags) rather than in strategic planning of comprehensive stabilization measures.

After the major floods in 1987 and 1988, a proposal for stabilizing the Jamuna River was developed by the China Bangladesh Joint Expert Team (CBJET, 1991; Zhou and Chen, 1998). The plan was developed after comparing the characteristics of the Jamuna River with the Yangtze River and the Lower Yellow River in China. It was concluded that the physical characteristics of the Jamuna were intermediate between these two rivers. Two alternative stabilization approaches were assessed:

1. Node control involves establishing control of the channel alignment and flow paths at a series of quasi-stable "nodes" along the river. The spacing and layout of the nodes takes advantage of naturally occurring (temporary) narrow sections by reinforcing these features to make them more permanent.
2. Bend control involves guiding the flow into a series of bends to establish a stable meandering pattern.

Both approaches involve training the river using a series of groynes, spur dikes, or revetments. The bend control concept was expected to require fewer protective works and less scour protection. The

Phase 1 plan was primarily based on the bend control approach. Figure 14 shows the layout of the scheme. Some key features of the plan are as follows:

- Priority was given to strengthening and raising the Brahmaputra Right Embankment. Flood protection on the left bank started from the offtake of the Old Brahmaputra and extended downstream to the offtake of the Dhaleswari River. The distance between the left and right bank embankments averaged 12.1 km.
- The width of the main channel was reduced by approximately 20% (to approximately 5 km), while the width of the floodplain was increased by the same amount.
- Implementation of the river training works was phased. The Phase 1 stabilization plan focused on three classes of problems:
  - near confluences, such as the reach downstream of the Teesta River,
  - at critical offtakes (Old Brahmaputra River and Dhaleswari River), and
  - near important town centers and infrastructure.

A combination of bend control and node control was proposed, focused on the highest priority sections along the river. Work on the right bank protects the existing Brahmaputra Right Embankment from breaching. A new flood embankment was proposed along the left bank, set back from the bank protection.

Phase 1 involved constructing 71 km of river training works. The Phase 1 plan did not specifically address the issue of land reclamation; this aspect was deferred to a later stage after a stable river corridor had been achieved. It was indicated that completion of the plan would take several decades. In the early 1990s the Flood Action Plan (FAP 1) proposed a program to stabilize the Jamuna River that was largely based on the CBJET strategy. The time period for completing the works was 50 years.

River stabilization projects that were implemented in the 1990s focused primarily on controlling erosion along the right bank of the Jamuna River to protect the Brahmaputra Right Embankment from breaching. Halcrow (1994) developed the “hard point” concept, which involved installing a series of short protected sections of the riverbank. The proposed “hard points” were nearly 600 m long and were connected to the flood embankment over the floodplain with a 900 m long embankment (Figure 15). The land between adjacent hard points was allowed to erode, requiring the retirement of the flood embankments of up to one kilometer away from the riverbank at construction. Up to 19 structures were proposed in the plan, protecting the entire length of the Brahmaputra Right Embankment.

Four structures were built between the mid-1990s and 1998. The upstream spur and the longer hardpoint at Sirajganj suffered from repeated massive damages, while the two downstream “hard points” never came under serious attack. Despite extensive maintenance and re-construction efforts, the concept was prone to repeated failure due to rapid, deep scouring and insufficient understanding of the behaviour of scour protection aprons. Therefore, the remaining structures were not implemented and this approach was discontinued.

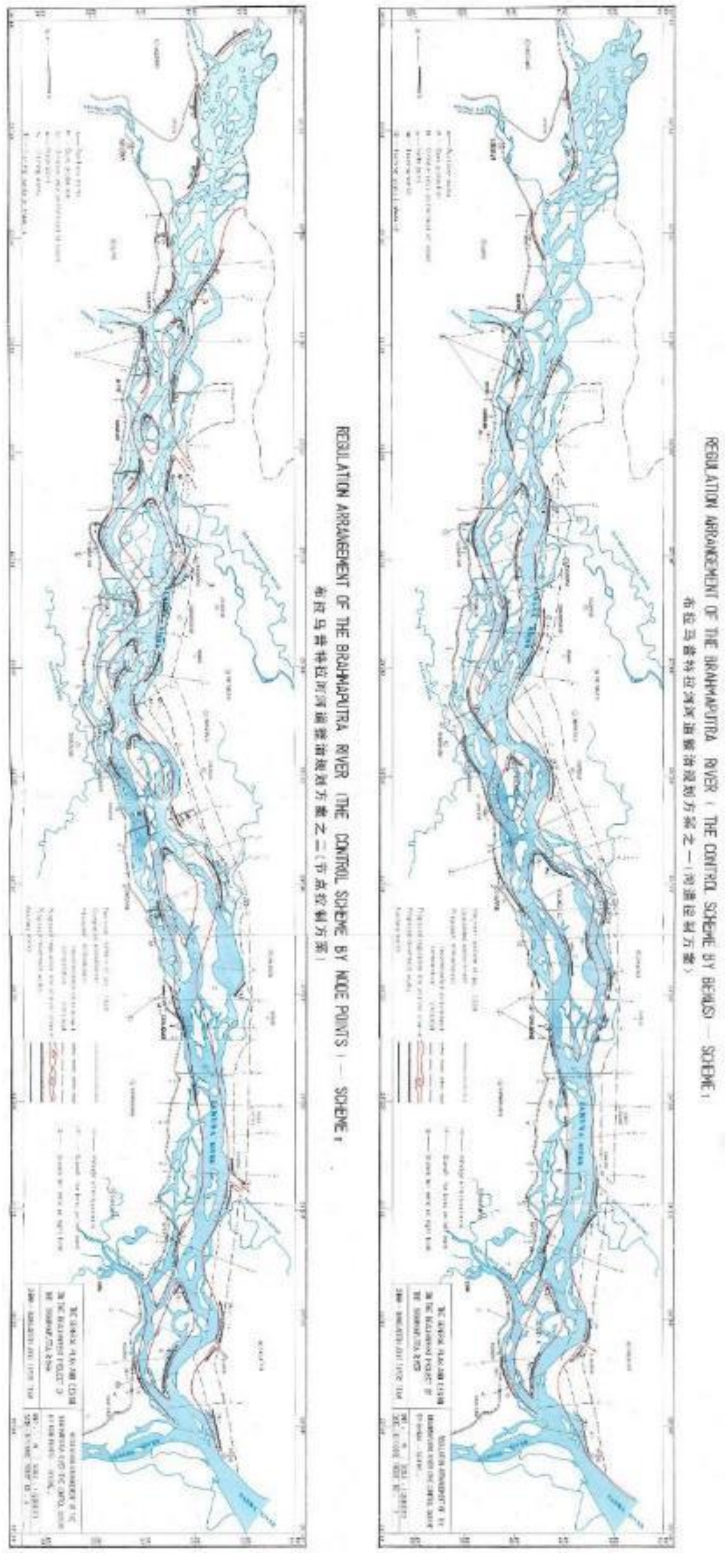


Figure 14: Phase 1 RSP, Jamuna River (CBJET, 1991).

During the early 2000s, the BWDB eventually adopted the use of long guiding revetments protected with sand-filled geotextile bags (called geobags) (Figure 16) as the most stable and cost-effective solution until today (BRTC, 2010). The key lessons learned during this period were:

- There is no stable riverbank protection in Bangladesh without adaptation and maintenance.
- Revetments result in half the scour depth during one season than protrusions (spurs and “hard points”) and therefore are less likely to fail. Localized failures do not result in major erosion losses when long revetments guide the flow parallel to the bank.
- Successful toe protection using falling aprons depends primarily on consolidated riverbank soils, the use of flexible elements reducing winnowing failure (the washing out of the fine underlying soil through gaps between the elements), and after launching all falling aprons requires upgrading to higher layer thickness, sustainable to winnowing failure.
- Flexible geobags provide the densest aprons after launching and are the elements of choice.

This work has still been mainly reactive in nature however, with the protection applied at critical sites experiencing or vulnerable to erosion. The applications to date have generally not addressed issues such as defining a preferred width or planform of the active river channels or incorporated significant land reclamation into the projects.

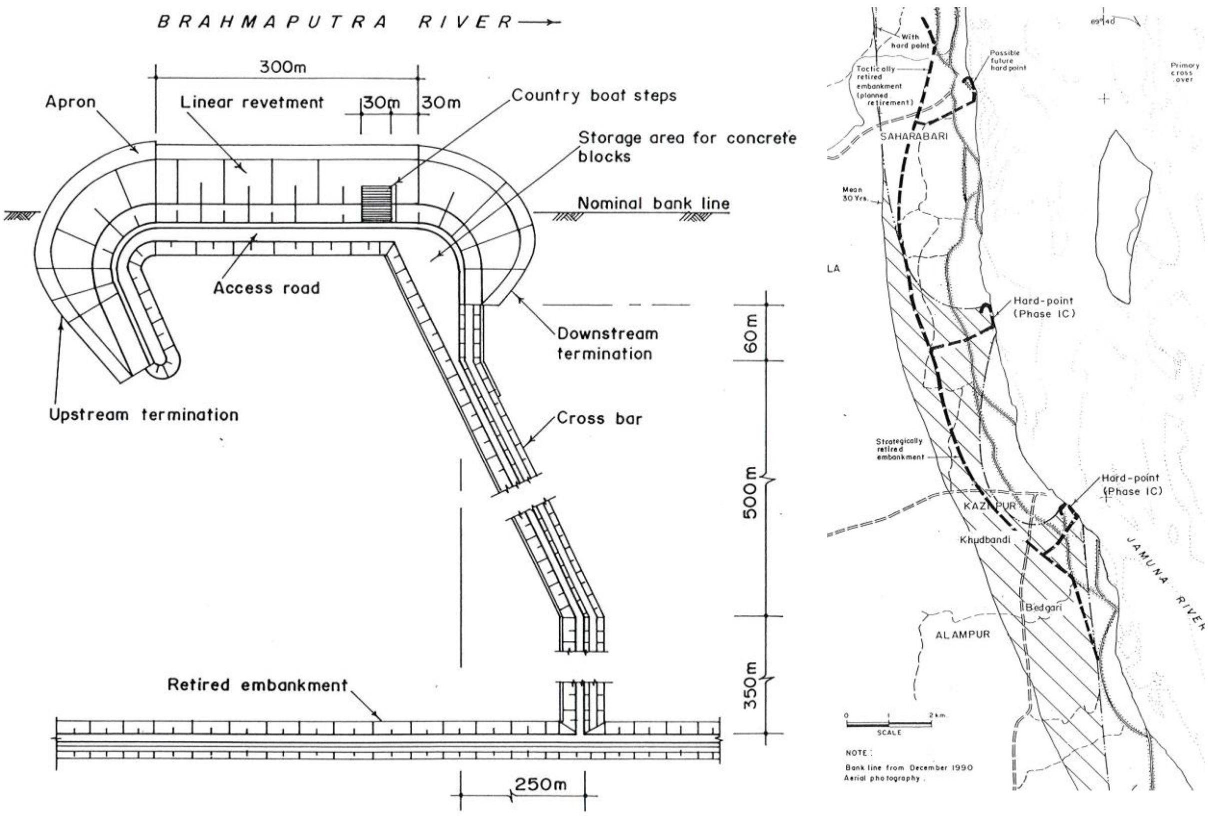


Figure 15: Hard point concept and plan showing a series of structures and resulting bank line changes (Halcrow, 1994).

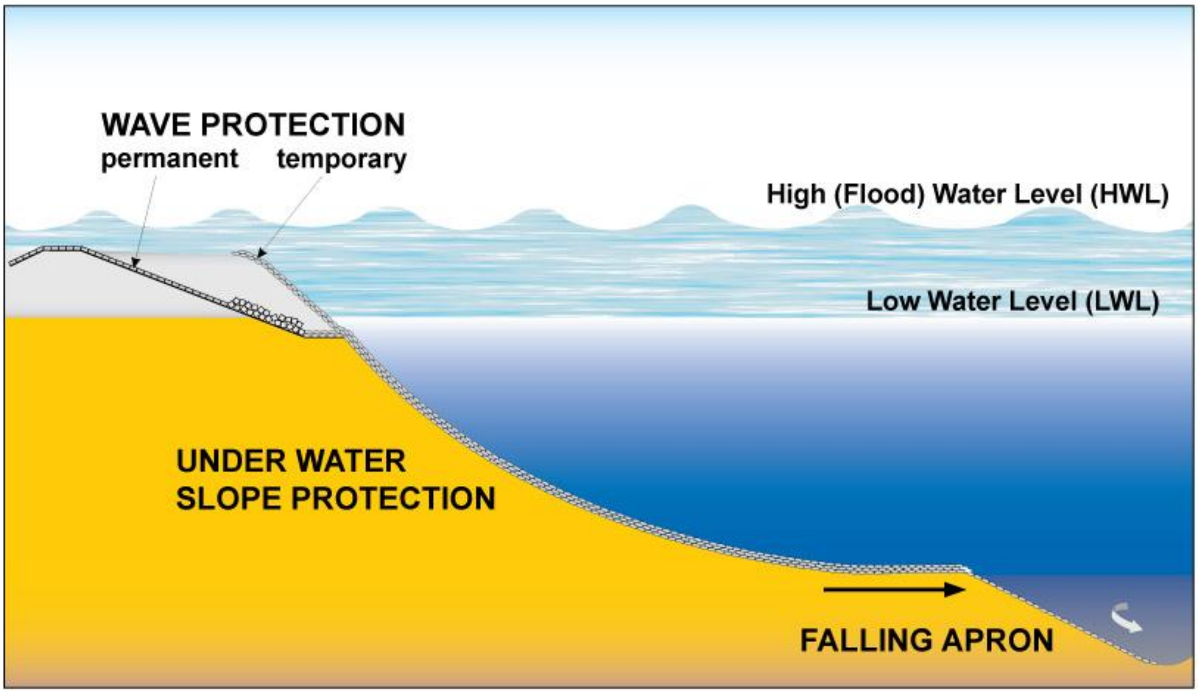


Figure 16: Long guiding revetments incorporating geobags (adopted from Oberhagemann and Hossain, 2010).

PART FIVE – FRERMIP RIVER STABILIZATION PLAN AND STRATEGY

13 REVIEW OF OPTIONS

Based on the review of previous experience in Bangladesh and abroad, four river stabilization options have been considered to guide the RSP.

13.1 Option 1 – Business as Usual

Conducting systematic local repairs and maintenance at eroding banks could result in a gradual, localized improvement to the security of flood control infrastructure if the work is continued over a sufficient length of time. However, since this approach is entirely reactive, the RSP's main goals and objectives could not be achieved in a time horizon of 30 to 50 years. Consequently, land loss due to bank erosion, and flooding leading to loss of life and property would persist. Discharges into main distributaries such as the Old Brahmaputra and Dhaleswari Rivers will continue to decline as will their potential to replenish ground and surface waters to arable land along their banks and to residential and industrial areas of the Dhaka Metropolitan Area. River transport will remain constrained particularly during the dry season. The potential to flush heavily polluted and congested surface waters will remain unexploited.

13.2 Option 2 – Long Reach River Training

This strategy involves substantial expansion of the current riverbank stabilization program by installing river training structures to protect high priority infrastructure, towns, and other critical sites such as distributary offtakes and tributaries. A more stable channel alignment would be developed using a combination of node control and bend control techniques using structures such as revetments or possibly groynes. Upgrading existing flood embankments and new embankments are set back from the stabilized river channel after channel stabilization is completed. The work would be implemented in phases, focusing initially on highest priority reaches of the river where ongoing erosion poses the highest risks and potential benefits are highest. This general approach is similar to the basic strategy proposed in CBJET (1991).

This approach does not specifically address issues of land reclamation or recovery of previously eroded floodplain land, restoration of important distributary channels, or improvement of the main river navigation channels. Therefore, a broader approach is needed to meet all of the goals and objectives of the RSP.

13.3 Option 3 – Channelization by Dredging

Dredging has been used on relatively small, gravel- and sand-bed rivers in Europe and North America, as a component of river stabilization work. It has not been widely used on large sand-bed rivers as a means to prevent bank erosion or to establish a preferred channel alignment and channel pattern. There are a number of drawbacks to this approach. On large sand-bed rivers transporting high sediment loads, dredging is costly both for the initial dredging but also for annual maintenance dredging in which the volumes can be as much as 90% of the initial dredging. The excavated material is mostly sand with little nutritive value and disposal is problematic. While there is some productive use of this material that includes raising areas planned for industrial development, constructing embankments, and filling geobags for bank protection, the requirement for these applications is relatively small. Much of this material ends up on land that is expected to produce agriculture products and in the short to medium term this material inhibits production. Considering the anticipated high costs associated with dredging as well as the negative impacts of spoil disposal, this approach is not considered to be an attractive strategy for stabilizing the main river channels in the region. Dredging still has an important role in terms of deepening and restoring the major distributary channels.

13.4 Option 4 – Stabilized Flood Corridor

This strategy involves developing a dynamically stable flood corridor that can safely convey the river discharge and sediment load while minimizing risks to infrastructure on the floodplain. The option involves using a combination of structural river training, land reclamation, embankment construction, and channel dredging. Establishing a stable corridor is not the same as channelizing the river or forcing it into an artificial alignment. A stabilized corridor will provide room for the river to adjust dynamically to changing flows and sediment loads, but will limit the lateral extent of migration so that damage to critical infrastructure will be minimized.

Riverbank erosion and river widening will be limited primarily by river training measures (mainly revetments). The alignment and spacing of these works will be planned so as to optimize and minimize the total length of protection that is required. This will include the application of bend control and node control concepts to promote the establishment of a stable planform. Some of the river training components of this option overlap with the strategy described in Section 13.2.

Achieving a more stable river corridor would permit construction of infrastructure to divert flow into distributaries. Strategically placed infrastructure, in combination with capital dredging, will guide the river within a restricted flood corridor. It will also result in a deeper channel with an increased discharge capacity, resulting in improved navigability. Deeper and more efficient main channels also have the potential to reduce flooding and recover floodplain land lost to erosion over the last 50 years. Through the concept of “building with nature”, which takes advantage of the natural process of accretion, lost land can be recovered while at the same time protecting the floodplain and providing opportunity for more secure settlement leading to economic development.

13.5 Comparison of Options and Selected Option

The four strategies are compared in Table 3. Of these, Option 4 (Stabilized Flood Corridor) specifically addresses all of the river stabilization goals and objectives described in Section 8. Option 2 (Long Reach River Training) meets some of the key goals of the plan related to stabilizing critical sections of the rivers, but does not take an integrated approach to dealing with other issues related to land reclamation and restoration and navigation channel improvements.

Table 3: Assessment of potential river stabilization options.

Criteria	Option 1 – Business as usual	Option 2 – Long Reach River Training	Option 3 – Channelization by Dredging	Option 4 – Stabilized Flood Corridor
Corridor stabilization	None	High	Low	High
Bank erosion	Continues	Reduced	Somewhat reduced	Reduced
Flood risk	Continues	Reduced	Somewhat reduced	Reduced
Distributary restoration	None	Minor	Yes	Yes
Enabling navigation	None	Minor	Yes	Yes
Transboundary impact	None (natural changes)	Minor	High (risk of river degradation)	Low (accelerated natural changes)
Maintenance	None	Yes	Very high	Some
Land recovery	None	Minor	Yes	Yes
Land-based productivity	None	Increase	Potential increase	Increase
Physical impacts	Continue	Substantial	High	Substantial
Environmental impacts	Continue	Moderate	High	Moderate
Social impacts	Continue	Moderate	High	Moderate
Sustainability	None	High	Low	High
Cost	Recurrent	Moderate	Very high	Higher investment, low maintenance

14 THE RIVER STABILIZATION PLAN

14.1 Elaboration of the Stabilized Flood Corridor

The RSP is based on the lessons learned from river training work carried out in Bangladesh over the last 60 years as well as international experience gained on other large rivers such as the Yellow River. The RSP utilizes a mix of engineering and “building with nature” technologies applied throughout the year, which is also in line with Government priorities[1]. The technologies to be implemented are described as follows:

1. **Construction of long guiding revetments** provides a reliable boundary between the floodplain and the river channel. These revetments have a demonstrated self-dredging ability and result in a more predictable channel pattern even when only built along parts of the riverbank. The training structures will be constructed primarily using geobags due to

[1] The Prime Minister of Bangladesh highlighted in her speech for the World Water Day on 22 March 2018:
“There is no fixed boundary between river and floodplain. Defining the river course, boundary between land and river, planform and buffer zones are essential for the management of the major rivers.”
“The government, since taking over, has given special emphasis on the restoration and development of natural wetlands, revival of the river and navigation through dredging … maintaining the connectivity between the river and the floodplain, creating a buffer zone along the riverbank for the protection of the environment and ecosystem.”
“There are no alternatives to nature-based solutions for facing the mounting challenges of water resources management. … We should introduce innovative nature-based solutions for water resources development and management in addition to the conventional solutions.”

their proven performance and lower cost. This technology is classified as an engineering structural measure.

2. **Multi-purpose dredging** supports a more stable river environment. Dredging extracts the sand fraction of the transported river sediment; this bed load represents about one-quarter of the total sediment. Dredging improves dry-season navigation and supports the construction of riverbank protection and embankments. Dredging spoils are also used for the construction industry, to close unwanted channels, and to provide material for raising industrial land above high flood levels.
3. **Sediment harvesting** extends river stabilization into the flood season by capturing the dominant component of the sediment the river is transporting – the suspended sediment. At high flood levels, the deposition of suspended sediment is accelerated through indigenous techniques such as reed plantations at desired locations. The land raised in this manner would be mainly intended for agriculture. Unlike bed load, the finer suspended sediment contributes to the fertility of agriculture land.

The combination of the above three technologies facilitates an integrated, phased approach with a reduced cost since it actively utilizes natural processes in the stabilization effort. In conformity with ongoing works (for example FRERMIP Tranche-1 from 2016 to 2020), riverbank protection will provide the backbone for stabilizing the Lower Jamuna River channel while continuing the development process of longer-term sustainable land accretion. Applying the three techniques to address different problems along a river course results in following seven specific activities:

1. **Riverbank protection**: Geobag revetments are the most cost-efficient and sustainable riverbank protection developed to date in Bangladesh. This notwithstanding, continued refinement is required with respect to construction on loose soils and an increase in safety levels for more productive land use. Further refinement is also required for the hard protection above-water which represents about 60% of the cost but protects less than 20% of the vertical height of the bank (measured from riverbed to top of bank). The stabilizing effect of riverbank protection has been demonstrated in the Lower Jamuna River, where the deeper channel reaches are now associated with riverbank protection works, while they were exclusively associated with channel confluences in the unprotected river of the 1980s (see for example Klaassen and Vermeer, 1988).
2. **Sediment redistribution**: Bifurcations are characterized by dynamic distribution of water and sediment in different ratios. This poses challenges when attempting to stabilize the distribution of both for a long-term stable bifurcation, as well as when attempting to close a channel by overloading one branch with bed material sediment. The latter is dependent on a recurrent process of dry season dredging. Stabilization consists of a combination of riverbank protection and dredging to obtain a geometry that provides long-term stable distribution ratios at stable bifurcations.
3. **Land accretion**: Land at higher elevations is more productive and consequently has a higher value. The natural process of depositing suspended sediment load typically accounts for land levels above the two-year flood level alongside the river and is often higher than the

floodplain. This land is termed as a “natural levee”[2]. The deposition process can be accelerated through reed plantations that promote more rapid settlement of the fertile silts and clays. Floodplain development to levels above high water levels depends on artificial fills, typically through the dredging of bed load (sand).

4. **Flood embankments**: Bangladesh has built thousands of kilometers of flood embankments since the mid-1960s. These generally provided for water exchange through regulators as well as freeboard for water level uncertainty and wave run-up, and in a few cases, fish pass structures. Improvements in embankment design include the incorporation of infrastructure to stabilize the riverbank, analysis related to extreme geotechnical conditions, and an all-weather road surface that facilitates both maintenance of this linear infrastructure and transportation to otherwise inaccessible areas.
5. **Navigation**: Lower water velocities combined with more stable river morphology makes navigation more practicable in the dry season. Nevertheless, each year these large rivers, particularly the Jamuna, require dredging to provide a navigable channel. Bangladesh and India have agreed on a five-year dredging contract between Sirajganj and Kurigram. This dredging will provide valuable long-term experience. An idealized stable channel, for example as achieved in the Rhine or Mississippi Rivers, consists of two types of river training works: protecting against the erosive forces associated with flood flows, and providing a long-term stable and predictable dry season channel. While the former is addressed by bank protection, the latter is intended by permeable structures, for example low groynes with the intention to reduce navigation dredging.
6. **Stabilizing Offtakes**: In particular, the offtakes of the Old Brahmaputra and multiple Dhaleswari channels are characterized by extremely variable inflows of water and sediment depending on the location of the main channels. Even so, these offtakes play a major role in providing Bangladesh’s North-central Zone, including the capital city, with fresh water during the dry season. The sequence of activities to restore and manage water and sediment intake to these offtakes is first to stabilize the main river channel. The next step is to establish the best offtake location, which would normally be downstream of an outer river bend. Only then would the distributary be restored, meaning bed levels have been lowered to efficiently transport dry season flows.
7. **Tributary geometry**: Tributaries are mostly stable and few in number. The largest are the Dharla, Dudhkumar, Teesta, Hurashagar, and Ganges. These are all on the Jamuna right bank. The location of their entry points into a potentially more stable river corridor needs to be secured. This will require interventions both in the current river corridor as well as upstream in the tributaries. Existing and planned barrages influence discharges and present challenges in securing stable entry points.

[2] Measurements in the area of Kaijuri where the Brahmaputra Right Embankment eroded in the mid-1990s, show that the deposition forms an around 2 km wide natural levee, about 2 m above the original floodplain level, reaching roughly the 2-year flood level (Fichtner and NHC, 2015; Annex A Volume 1).

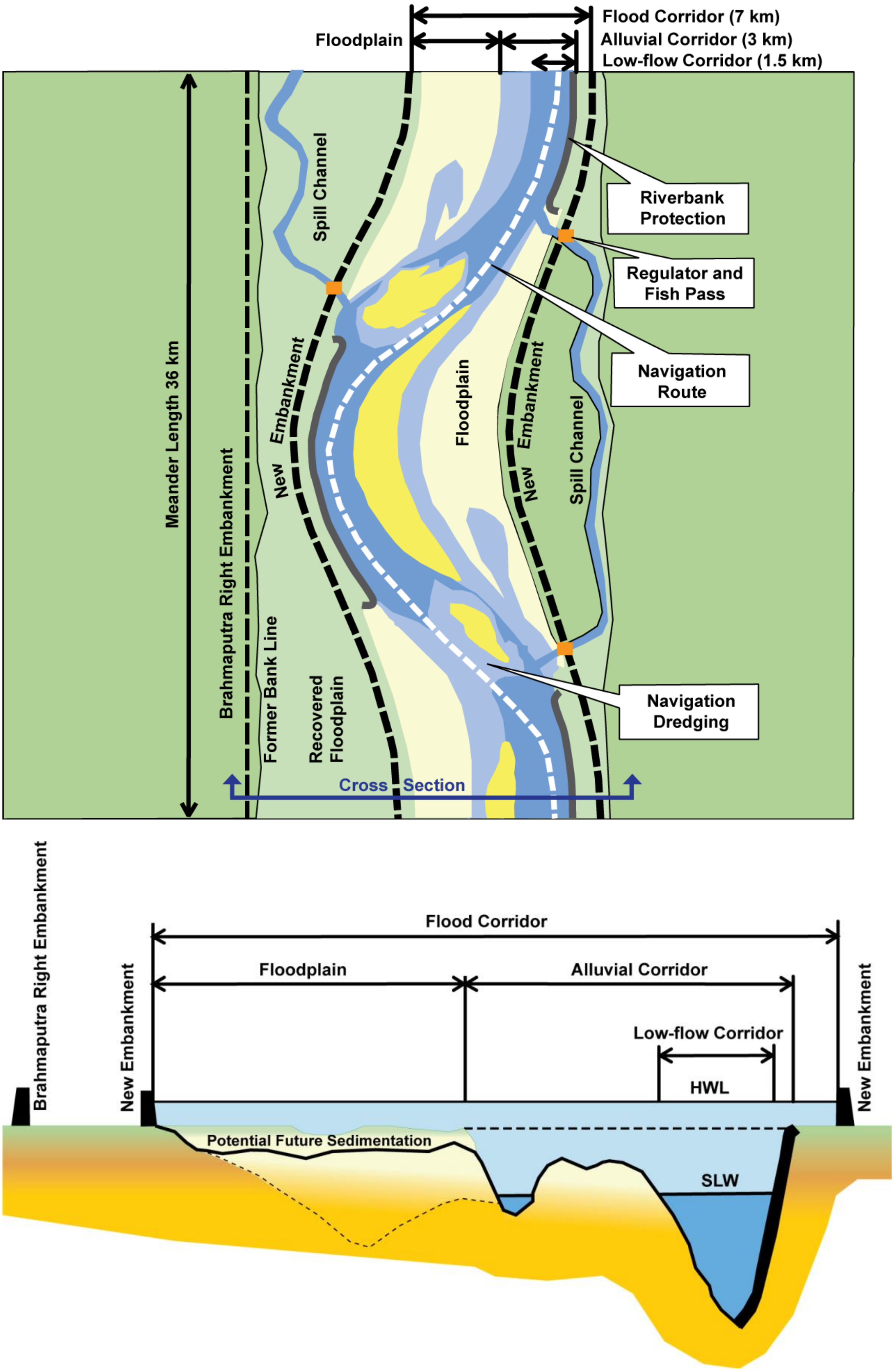


Figure 17: Schematic of alluvial corridor and flood corridor concepts (ISPMC).

14.2 River Stabilization

The approach involves establishing a dynamically stable alluvial corridor that conveys most of the river's sediment and a wider flood corridor that can safely convey extreme floods (Figure 17). The extent of the flood corridor is defined by the distance between the new or existing flood embankments along the riverbank. The entire area within the flood corridor might be reworked by erosion, some areas frequently (the river or alluvial corridor) and some areas only sporadically (the flood corridor). Preliminary estimates for the dimensions of the corridor are presented inTable 4.

Table 4: Preliminary estimates of corridor dimensions.

River	Alluvial Corridor Width (km)	Flood Corridor Width (km)
Jamuna	3	6.0 to 6.5
Padma	4	8.0 to 10

It is expected that these dimensions will be refined and modified as new information becomes available during the subsequent phases of the project. Therefore, in this report the dimensions are considered as tentative estimates rather than as final design parameters.

The method of bend control has been adopted as the preferred approach for stabilizing the overall alignment and planform of the rivers. This approach limits the overall length of bank protection to approximately 30% to 60% of the total reach length and also allows for some dynamic adjustment of the channel pattern and channel alignment. Adopting this method does not necessarily require confining all sections of the river into a single, narrow meandering channel. In some reaches it may be feasible to establish or maintain a single channel. In other sections, two or more branches or an anabranched planform may require less maintenance and be more stable in the long term. In addition, other bank protection methods may be appropriate for strategic locations.

14.3 Char Land Recovery

Identified methods for accelerating land reclamation include:

1. **Flow realignment by pilot dredging:** Excavate pilot channels to realign flow paths to create new localized deposition zones.
2. **Structural measures**: Construct structures (cross-bars or low berms from dredge spoil) on chars or along banks to promote local deposition and land accretion.
3. **Dredge spoil disposal:** Pump dredge spoil into designated reclamation areas to create new land.
4. **Acceleration of natural floodplain accretion**: Identify deposition zones where floodplain accretion is occurring and then accelerate the rate of accretion by "harvesting suspended sediment" through reed plantations and other bio-engineering methods.

The land recovery process requires a two-step approach:

1. Stabilization starts with the closure of a bank line channel at a bifurcation upstream of the char to be attached to the floodplain. The initial dredged closure dam should have a crest height close to the floodplain level such that during the beginning of the monsoon, flow into the bank line channel is blocked and directed into the dredged, preferred channel. Later, as

the closure dam is overtopped and breached, the flowing water transports the sand downstream into the bank line channel. This in turn reduces the cross section of the bank line channel. The reduced bank line channel then flows more slowly, promoting further deposition. Depending on the length and size of the bank line channel, the process may need to be repeated over several years. Where the char land is close to the floodplain or already attached the process is more rapid.

2. The vertical distance between typical char land and the floodplain is in the order of two meters. This means that the recovered land is typically flooded for some time during each flood event. To promote deposition of the suspended sediment transported in these flood waters, reed plantations are established to reduce flow velocities and promote deposition of the suspended sediment load. It should be noted that harvesting suspended sediment has the potential to increase downstream erosion, which must be a consideration in how aggressively sediment deposition is promoted.

Past experience (NHC, 2013) demonstrated a ten-year time frame for reclaimed char land to approach the level of floodplain after recovery operations. However, this experience is both limited and site-specific and therefore not representative for the entire region. There are several outstanding issues that limit assessment of the effectiveness, impacts, and benefits of land recovery. These limitations include:

1. The present sediment load and size distribution of the load are largely unknown.
2. The rate of sediment accretion in the recovered areas is uncertain.
3. The effect of potentially very large rates of accretion on the river's overall sediment budget is uncertain.

Error! Reference source not found. Table 5 provides an estimate of the maximum potential for char land recovery within the project area. The time period required to achieve the recovery is unknown.

Table 5: Maximum potential land recovery in project area.

Reach	Right bank		Left bank		Total	
	Number	Total area (10^3 ha)	Number	Total area (10^3 ha)	Number	Total area (10^3 ha)
1	2	31	2	18	4	49
2	1	1	1	26	2	27
3[1]	3[1]	15+20[1]	1	5	4	40
4	1	16	2	10	3	26
5	0	-	1	19	1	19
Total	**7**	**83**	**7**	**78**	**14**	**161**

[1] Centre char island land recovery of 20,500 ha included in this total area in reach 3

14.4 Stable Offtakes

Distributary offtakes are generally silted and as a result do not convey water inland from the main rivers during most of the six-month dry season. This affects a significant population. While water from the distributaries can be used directly for irrigation and some of the growing number of industries, it is principally needed to replenish ground water. The latter provides water of a higher quality that is potable. Experience on the Pungli River offtake illustrates the difficulties of establishing dry season flows. Two dredging attempts failed because of the rapid siltation resulting from an unsuitable offtake.

Stable offtakes depend on a stable main river planform. Ideally, the offtake locations can be developed at the downstream end of protected river bends. These provide predictable flow conditions and allow the construction of offtake geometries that attract the right mix of water and sediment for stable downstream distributary channels. Flood barriers, which become part of the embankment line, are needed to restrict excessive flood flows but would allow unimpeded lower flows. Inflatable rubber dams are a technology that has been tested and is appropriate. The flow will be unimpeded until a 5- to 10-year flood level is reached and then would be restricted through gradual inflation of the rubber dam. This approach ensures that the natural processes of floodplain inundation and sedimentation remains largely unhampered and only infrequent high flood peaks will be capped.

After providing a stable offtake, work on restoring the distributary can take place. Initially capital dredging will restore sufficient cross-sectional area to provide a defined amount of dry season flow. The dredge spoil management will require special attention, as it cannot be deposited on the densely used floodplains. The substantial percentage of sand will be attractive for the construction industries and can be sold to recover some of the dredging cost. As the overall annual discharge in the distributaries will increase after dredging, the distributaries will require local riverbank protection to maintain their shape. Here geobag revetments as well as other techniques could be applied. Successful tests have been conducted in Bangladesh with top and bottom screens. Specific trials will identify suitable techniques that help to restore the marine environment and provide safe navigation conditions where necessary.

14.5 Navigation Channel Improvement

Navigation improvements on the main rivers require a more stable channel alignment and a deeper channel during the dry season. Where the channel alignment can be stabilized and the riverbank is protected, bed erosion takes place. This effect can be observed along the long revetments already existing in Reaches 3 and 4. The basic river conditions, however, will not change. The sediment load will continue to be variable and depositional patterns uncertain. As well, the characteristics of the monsoon will remain unpredictable. These factors will require consideration at locations where the main channel moves from one bank to the other and which are prone to sediment deposition.

For the foreseeable future, navigation improvement will depend heavily on recurrent dredging activities during the dry season. Dry season navigation dredging has so far provided the only solution to restore navigation channels. The Government has initiated navigation dredging activities in the more unpredictable Reaches 1 and 2. The first results of this work are expected during the 2019/2020 dry season. Even after substantial river stabilization, dredging will remain the technology of choice in a stabilized river corridor. Only gradually, and with a substantially deeper understanding of the sediment load as well as sustentative experience with the behavior of the largely stabilized corridor, can additional river training measures be implemented to improve navigation conditions at stable crossings.

Dredging is attributed great importance by the Government. Its main purpose is to restore river flow in most smaller rivers of the country, and to aid dry season navigation. Within the context of main river stabilization, dredging may be used for:

- Underwater slope preparation for riverbank protection works, particularly on unconsolidated loose char soils;
- River training purposes including forming pilot or cut-off channels and choking (overloading with sediment) unwanted channels;
- Embankment construction (sand core);
- Low-flow navigation channels;
- Speeding up land reclamation of char lands by filling with dredged material; and
- Speeding up offtake and distributary redevelopment by increasing capacity and flows along the distributaries for improved water supply as well as inland navigation.

14.6 Planning Reaches

The river system has been subdivided into five main and three transitional reaches (Figure 18) for describing river morphology and for various design purposes. In order to illustrate the adaptive nature of the plan, these reaches have been grouped into two main areas:

1. **Upstream planning area**: Jamuna River upstream of Bangabandhu Bridge, including Entrance Reach, Reach 1 and Reach 2.
2. **Downstream planning area**: Jamuna River downstream of Bangabandhu Bridge and Padma River, including Reach 3 through Reach 5.

The reason for this division is that the Jamuna River in Reach 1 and Reach 2 is more unstable and braided in character than the downstream reaches. There is also more uncertainty about the feasibility of channelizing the upstream reaches at the present time. Further downstream, the river has been in the process of developing a more stable alignment over the last few decades.

The type of actions and timing of actions in this upstream planning area are expected to be different from in the downstream area. Furthermore, the costs and potential benefits of the works in the two areas are expected to be very different. The approach for dealing with these issues is illustrated conceptually in the sections below using a dynamic adaptive planning approach.

14.7 Future Scenarios and Tipping Points

The future stability of the river will be governed by hydro-geomorphic controls (primarily water and sediment inputs) as described in Section 7.5. Three plausible future scenarios were described, ranging from a decrease in sediment inflows and a trend towards a naturally stabilizing channel (Scenario 1) to a recurring sediment wave that would involve an increase in sediment loads, a decrease in channel stability, and an increased tendency towards braiding (Scenario 3). The RSP must allow for a range of future scenarios, which may require modifying project elements, alternatives and implementation schedules if necessary while still meeting the overall plan objectives.

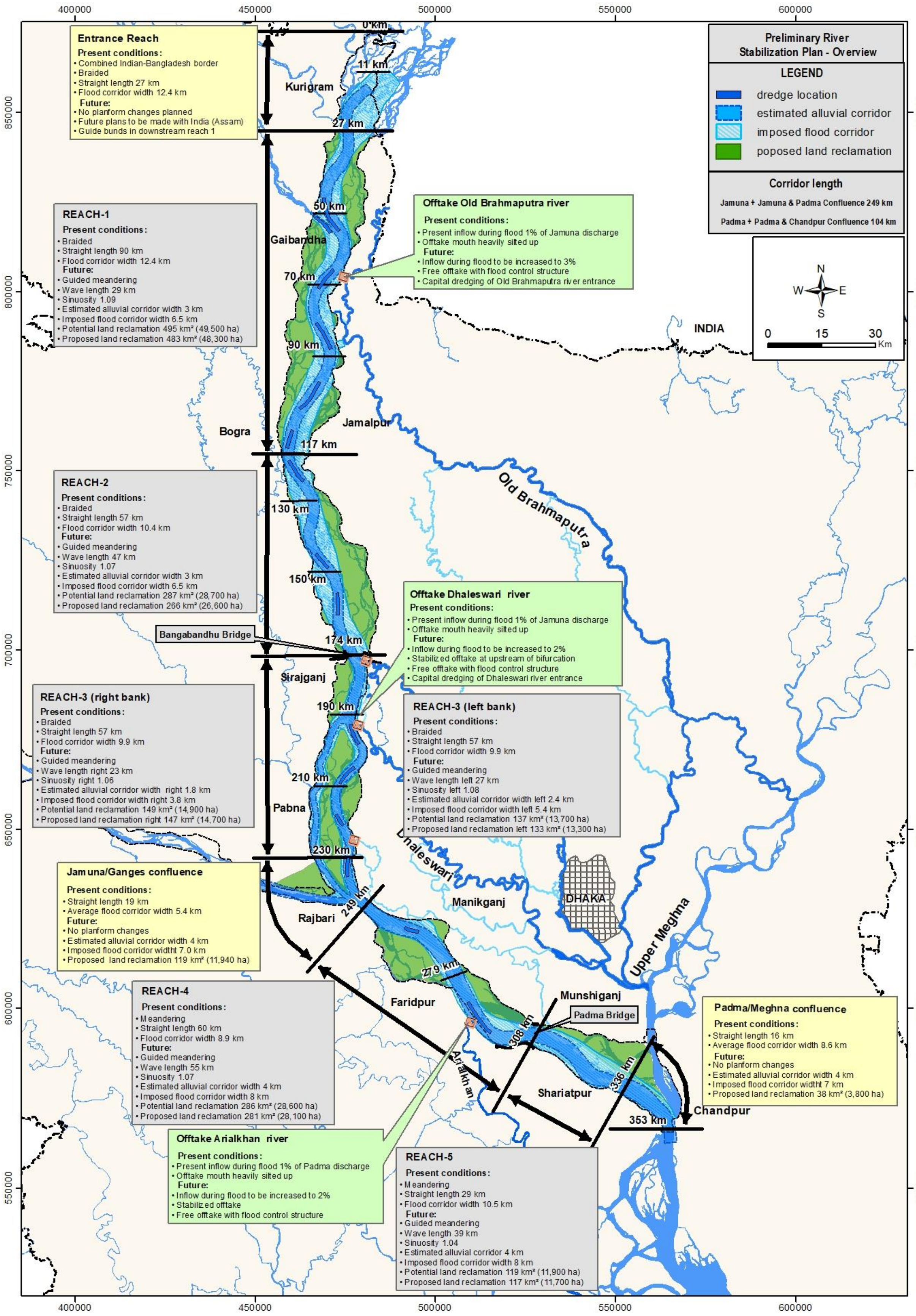


Figure 18: Details of the RSP reaches (ISPMC).

The term "tipping point" refers to the condition where hydro-geomorphic controls change so much that the implementation program requires modification. Other tipping points related to socio-economic or environmental factors may also be eventually defined. However, at this point only hydro-geomorphic controls are discussed since these will govern the effectiveness of the interventions and many of the impacts to the surrounding biophysical environment.

Two types of tipping points could occur. If the overall stability of the river system continued to improve as a result of a long-term decline in sediment supply (Scenario 1), then an opportunity arises to accelerate reclaiming former floodplain land and narrowing the channel. This situation is considered an opportunistic tipping point. Based on the morphological studies described in Section 6.4, it is believed that the Padma River (Reach 5 and Reach 4) and the Lower Jamuna River (Reach 3) have already experienced this situation. If the channel remains highly unstable or sediment loads and flows increase over time (Scenario 3), then a point may be reached where the focus of river training measures will need to be directed towards maintenance of the existing corridor, rather than attempting to narrow the channel or modify its planform substantially.

14.8 Adaptive Planning Pathways

The necessity of using an adaptive planning approach was described in Section 4. This section of the report illustrates how components of the plan may evolve over time in response to future hydrological-sediment input conditions (the future scenarios described in Sections 7.5 and 14.7).

14.8.1 Approach

The Deltares Pathways Generator software was used to describe implementation of the alternative project actions over time under two future scenarios (described previously in Section 7.5). To cover the range of potential conditions, only Scenario 1 (declining sediment and water inflows) and Scenario 3 (increasing sediment and water inflows) were used.

In order to simplify the method, the river training component of the plan has been considered as the primary intervention. The other major components of the plan, such as dredging, land reclamation, and flood control are considered as subordinate components, since they all depend to some extent on the river stabilization measures to be carried out before they can be fully effective. Table 6 summarizes the alternative actions that could be carried out over the course of the plan in response to different future scenarios.

The first river stabilization action (maintain and extend existing bank protection infrastructure) involves expanding the present practice of constructing long geobag revetments in response to erosion damage and potential threats to new areas along the river. This action is characteristic of the work that was carried out in the 1990s and early 2000s during the period when the Jamuna River was most unstable and was in a period of widening. Expanding this approach and given sufficient time, a large percentage of the active bank line would be protected against erosion, which would allow a more reliable operation of flood control projects and a reduction of embankment breaching. However, the stable bank line would follow the present bank, so that there would be little opportunity to reclaim previous floodplain land that was lost to the river.

The second action (strategic river stabilization) involves using a combination of bend control and other localized bank protection works to establish a more stable channel at critical sections of the river. The location and timing of implementation are based on a prioritization process. Some of these works could be initiated opportunistically, by identifying areas that display a natural tendency to establish more stable channel alignments or where banks are naturally accreting. These actions are focused primarily on establishing a stable corridor and channel alignment rather than reclaiming land. Land reclamation would be carried out opportunistically by accelerating natural accretion in target areas and by pilot dredging to promote local deposition zones. The work would increase the security of existing flood embankments against breaching and could promote expansion of new embankments into presently unprotected sections of the floodplain.

The third action involves continuous bend control to establish a single, guided meandering channel within a stable alluvial corridor. This action allows for the maximum opportunity to reclaim land and to produce a stable defined navigation channel. New flood embankments would be constructed along the newly reclaimed floodplain land close to the stabilized channel. The concept of transforming a highly active, braided sand-bed channel into a narrow, single, low sinuosity channel would be an unprecedented undertaking. A series of pilot-scale tests would need to be carried out before fully undertaking this action along the entire length of the river.

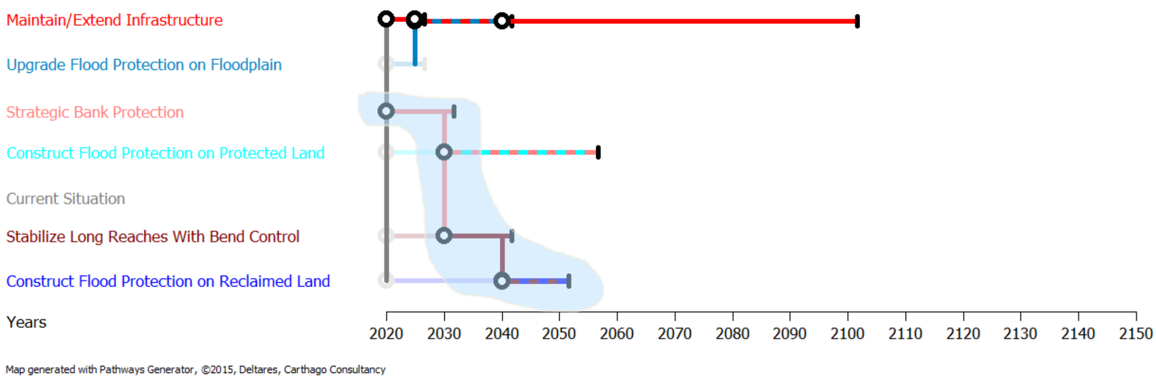
Table 6: Alternative actions.

Components	***Actions***	***Description***
	Primary Actions	
River stabilization	Maintain and extend bank protection infrastructure	Build, repair and extend revetments in response to failure/ new attack
	Strategic bank protection	Bend control at key sites and stabilization of offtakes and tributary junctions
	Stabilize long reaches with bend control	Full implementation of stabilized corridor plan to produce single or branched channel and reclaim active areas of present channel zone
	Subordinate Actions	
Navigation and dredging	Main river dredging	Mixed purpose including navigation channel improvement, pilot channel excavation, construction of bank protection
	Distributary channel dredging	Navigation channel improvement
Land reclamation	Accelerate natural accretion in former floodplain areas that are currently in the process of self-stabilizing	
	Pilot dredging to re-direct flow creating new accretion	
	Dredging to fill low land behind new structures	
Flood control	Upgrade existing embankments	
	Construct new embankments on protected floodplain	Delay until reliable bank protection established
	Construct new embankments on reclaimed land	Delay until accretion of reclaimed land is achieved

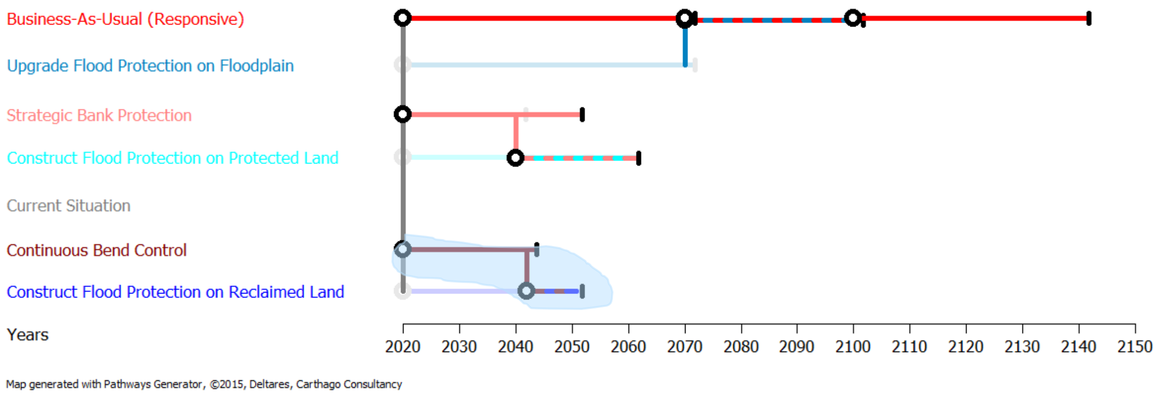
14.8.2 Pathways in the Downstream Planning Area

Figure 19 (Top graph, below) shows potential pathways in the downstream area under Scenario 1. The labels of the three river stabilization actions correspond to the description in Table 6. The graph shows all three river stabilization actions can be implemented. It is assumed that it would take much longer to achieve the plan goals if the bank were stabilized simply by expanding current practice than by using the other two actions. The suggested preferred pathway is shaded in blue. This involves starting with strategic river stabilization actions (as defined in Table 6) then switching to the narrow, guided meandering channel after initial pilot testing of the bend control methods and reclamation methods have been confirmed.

Figure 19 (Bottom graph, above) shows the same area under Scenario 3. The plot shows a new sediment wave would further delay completion of bank stabilization works if the only actions followed current practice. This plot shows that full implementation of the RSP could still be carried out, but the time required would be longer than with Scenario 1. A period of primarily maintenance actions may be required during the peak period of the wave. Whether this is realistic would depend on the magnitude of the disturbance and the timing of the implemented works.



Scenario 1: Decreasing sediment and water inflow with trend towards increased channel stability



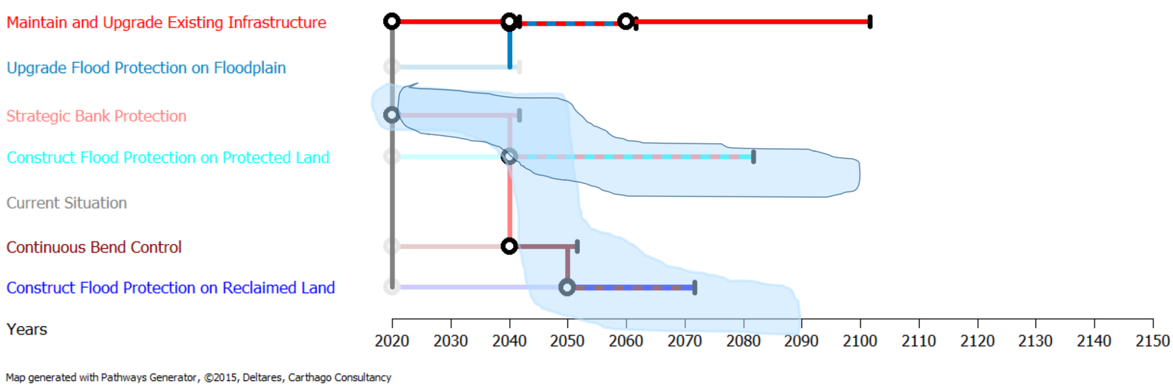
Scenario 3: Increasing sediment and water inflow with trend towards decreased channel stability

Figure 19: Potential pathways, FRERMIP downstream planning area (ISPMC).

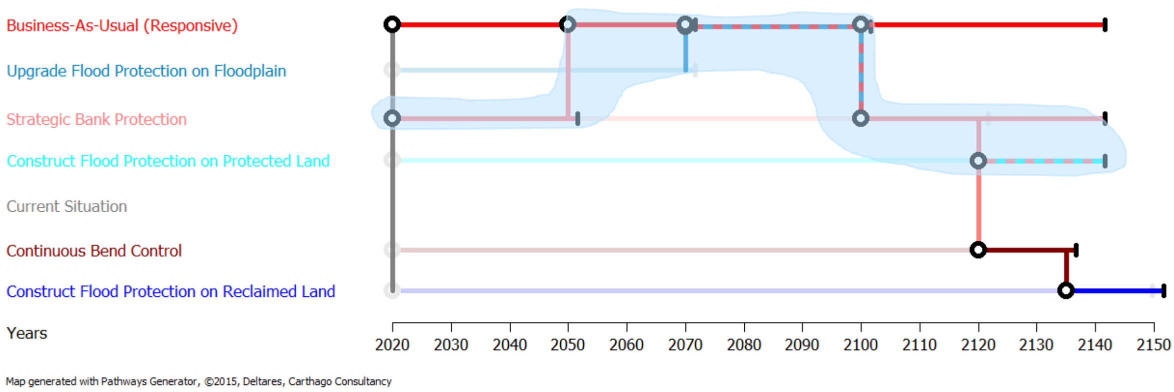
14.8.3 Pathways in the Upstream Planning Area

Figure 20 (Top graph, below) shows potential pathways in the upstream area under Scenario 1. The graph shows all three river stabilization actions can be implemented. Again, the action of expanding current practice requires the longest time frame to achieve a stable channel. Two potential preferred pathways are shaded in blue. The first involves implementing the strategic stabilization actions alone. The second involves a two phase approach, with Phase 1 starting with the strategic measures and Phase 2 commencing later, transitioning to further narrowing of the channel as the river's stability continues to improve. This approach is shown to achieve the faster completion of the project. It was assumed that starting by implanting full narrowing of the channel (labelled as "Continuous Bend Control") was not feasible under the present conditions.

Figure 20 (Bottom graph, above) shows the potential pathways under a future sediment wave. This shows the project starts by initiating the strategic river stabilization actions but as the channel stability deteriorates due to increased sediment inflows, the project must switch over to the current "maintenance" approach of responding to local failures and threats to infrastructure. After the wave passes, the project returns to implementing the strategic actions, resulting in a delay in completing the plan but ultimately achieving its objectives. The pathway associated with constructing a narrow, guided meandering channel (labelled "full bend control") must be deferred far into the future.



Scenario 1: Decreasing sediment and water inflow with trend towards increased channel stability



Scenario 3: Increasing sediment and water inflow with trend towards decreased channel stability

Figure 20: Potential pathways, FRERMIP upstream planning area (ISPMC).

14.8.4 Preferred Pathways

Based on the present understanding of the trends in channel stability and past response to river training activities it is assumed that all three types of river stabilization actions are presently feasible in the downstream planning area. Therefore, adaptive implementation in this area would involve prioritizing sites and opportunities for bank stabilization and reclamation works and pilot testing of new stabilization methods such as the bend control approach.

Given the present unstable nature of the upstream planning area, and the uncertainty of project effects, transforming the braided reaches (Reaches 1 and 2) into a single meandering channel is deferred, recognizing that a number of critical questions still need to be answered to confirm the feasibility of the approach. Additional information on hydro-geomorphic controls, pilot testing of bend control in braided sections of the river, and further assessment of land reclamation opportunities/limitations are required to finalize the best approach in this area. Upgrading and extension of existing bank protection could still be carried out while this work was underway.

15 REFERENCE PROJECT

15.1 Background

In 2017 the study team developed a preliminary layout and design for a fully completed project, based on the present configuration of the river. Details of the project are shown in Figure 18. The project is aspirational in nature, representing a hypothetical future with the river transformed into a stabilized meandering channel and former char land reclaimed, converted to floodplain land and protected by flood embankments.

The design parameters for the scheme are preliminary and are based on the best analysis and expert judgement as documented in a number of Supplementary Annexes of the FRERMIP team. This Reference Project has been used to provide a basis for estimating the total costs and project impacts.

15.2 River Training Design Concept

The training structures will be constructed primarily using geobag revetments due to their proven performance, fast construction, lower cost, and high adaptability. The protective system typically consists of four layers of geobags, ranging in weight from 125 to 250 kg. This layer provides the combined advantage of being a filter layer to retain the fine, easily erodible subsoil, and stable when in high velocity flows. The riverbank protection will be placed preferably along outer curves that are located in conformity with the future desired channel pattern. Since the final river depth can be determined with reasonable accuracy and geobags provide a very reliable cover layer, the stability of the work is principally dependent on the quality of the underlying subsoil. To accommodate the various underlying subsoil conditions, four different design standards will be adopted (Figure 21). These design standards are based on Bangladesh experience with major works:

1. Consolidated riverbanks and beds (riverbank design A, river bed design A) – example Jamuna-Meghna River Erosion Mitigation Project, riverbank protection alongside the Pabna Irrigation and Rural Development Project (ADB, 2002): permanent slope treatment to the riverbed level existing at the time of construction, secured against future bed deepening and toe scour through an apron. The apron provides sufficient quantities for launching to the design scour in single layer. Typically, these aprons are around 15 m wide.

2. Consolidated riverbanks with looser bed material (riverbank design A, river bed design B) – example River Bank Improvement Project (Fichtner and NHC, 2015): permanent slope treatment to the riverbed level existing at the time of construction, secured against future bed deepening and toe scour through a wide apron. The wide apron also addresses the issue of static flow slides resulting from rapid scouring. To this end, the apron is wide enough to restrict the flow slides within the apron width after deduction of the quantities for launching to the design scour in single layer. Typically, these aprons are around 50 m wide.
3. Unconsolidated riverbanks with consolidated beds (riverbank design B, riverbed design A) – example Bangabandhu (Jamuna) Bridge guide bunds (Tappin et al., 1998): permanent slope treatment on dredged slopes reaching to consolidated bed strata, secured against future bed deepening and toe scour through an apron. Slopes are typically dredged to an angle of 1V:6H to arrive at practical dredging progress. The apron provides sufficient quantities for launching to the design scour in single layer. Typically, these aprons are around 15 m wide.
4. Unconsolidated riverbanks with unconsolidated beds (riverbank design B, river bed design B) – example Padma Bridge river training works (Maunsell|AECOM, 2011): permanent slope treatment on dredged slopes reaching to consolidated bed strata, secured against future bed deepening and toe scour through a wide apron. Slopes are typically dredged to an angle of 1V:6H to arrive at practical dredging progress. The wide apron also addresses the issue of static flow slides resulting from rapid scouring. To this end, the apron is wide enough to restrict the flow slides within the apron width after deducting the quantities for launching to the design scour in single layer. Typically, these aprons are around 50 m wide.

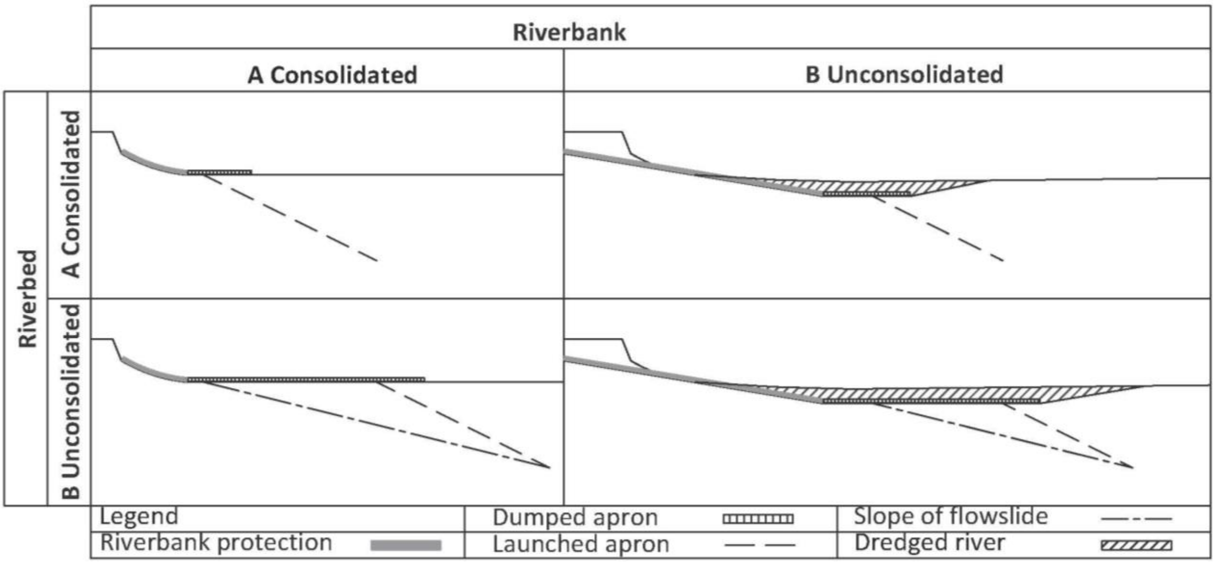


Figure 21: Design standards for various riverbank and riverbed compositions (ISPMC).

15.3 Assumptions and Vulnerabilities

An underlying assumption of the Reference Project is that the main rivers are already in a process of slowly narrowing in response to the passage of the sediment wave generated by the 1950 Assam earthquake as illustrated in Figure 6 and Figure 7. Nevertheless, future changes to the sediment inflows or other hydro-geomorphic controls on river stability could affect the performance of planned interventions. Changing sediment-water inflows during the implementation period could require revising design parameters and assumptions about preferred channel patterns and channel dimensions. For example, a substantial increase in sediment inflows and concurrent increase in channel instability in some reaches could require revision of the location and the number of guiding revetment structures.

A reactivation of channel braiding and widening could even require reassessing the feasibility of imposing a single meandering channel pattern on the river. Similarly, a period of sustained channel accretion and naturally occurring narrowing in some reaches could provide opportunities for permanently stabilizing bank lines at relatively low cost. The ongoing evolution of the river in response to changing hydro-geomorphic controls will need to be accounted for during plan implementation.

There are a number of uncertainties that will need to be clarified during subsequent phases of the project which will likely result in changes to some of the RSP's proposed actions and design concepts. The potential effect of these issues on the project are described below.

The project aims to achieve an estimated 1,500 km^2 of land reclaimed through vertical sediment accretion on former char land. This will require approximately 5.7 x 10^9 m^3 (9.1 x 10^9 tons) of sediment accretion. The spatial distribution of sediment deposition and the time period required to build up the land to floodplain level are highly uncertain. Given the large volume of infilling required, it is expected that decades could be required for the deposition process to be completed. Much of this accretion is expected to occur in areas situated inland of the proposed flood corridor (Figure 17). To achieve the reclamation benefits, most accretion and land filling will need to be complete before the new flood embankments are constructed. This area is identified as "reclaimed floodplain" on Figure 17. Waiting for land accretion to be completed could delay the flood control benefits of the work by decades.

16 POTENTIAL IMPACTS OF PLAN IMPLEMENTATION

The economic, environmental and social impacts that are presented in this section are based on the Reference Scenario described above. The time frame associated with implementing the Reference Scenario stretches into many decades. Forecasting the long-term morphological response of the river to the proposed interventions, and anticipating the many driving forces that will impact the river such as earthquakes affecting sediment load and changes to basin hydrology, present numerous uncertainties. Because of this, an implementation plan is proposed for the first decade only.

16.1 Economic

16.1.1 Objectives and Approach

The main objectives of the economic assessment were to:

- Assess the economic feasibility of the reference scenario of the proposed RSP; and
- Assess the impacts of river uses and river stabilization on the national economy.

Conventional analytical methods were used in the estimation of direct benefits, costs and impacts of the RSP. The main economic benefits included:

- Mitigation of the loss of land, buildings and infrastructure due to riverbank erosion;
- Reduction in crop losses and damage to buildings/infrastructure due to flooding;
- Increased crop production in areas protected from flooding;

- Reclamation of char lands for the establishment of rural settlements as well as agricultural and industrial development, including the establishment of Economic Zones (EZs);
- Improved navigation and increased water transport along the river corridor; and
- Improved road transport services due to the construction of embankment roads.

Following the design of the interventions required for river stabilization and flood mitigation, capital cost estimates were prepared for riverbank protection works, dredging, flood embankments and roads along five reaches of the Jamuna and Padma rivers. The costs of rural settlements and the establishment of EZs on reclaimed char lands were also estimated. In addition, a phased implementation programme from 2020 to 2050 was prepared. Finally, the economic benefits of these investments and their impact on the national economy were also assessed.

16.1.2 Main Interventions

Table 7 summarizes the main interventions proposed for five reaches of the Jamuna and Padma Rivers.

Table 7: Main Interventions of the RSP by Reach.

River Reach	Riverbank Protection	Flood Embank-ment	Dredging		Low Spurs	Char Land Development	
			Construc-tion	Capital & Navigation		Rural Settlements	Economic Zones
Jamuna							
Reach 1	69 km	170 km	39 km	94 km	47 km	50,500 ha	
Reach 2	17 km	70 km	17 km	36 km	18 km	27,280 ha	420 ha
Reach 3	62 km	150 km	38 km	40 km	20 km	37,700 ha	120 ha
Padma							
Reach 4	25 km	140 km	12 km	28 km	14 km	9,100 ha	17,000 ha
Reach 5	32 km	70 km	21 km	0 km		16,000 ha	
Total	**205 km**	**600 km**	**127 km**	**198 km**	**99 km**	**140,580 ha**	**17,540 ha**

By 2035, it is envisaged that a total of 205 km of riverbank protection works will be constructed. In addition, 600 km of flood embankments will be built along the five reaches of the Jamuna and Padma Rivers by 2045. Capital dredging and dredging for navigation/construction will also be undertaken between 2020 and 2040 and a total of 198 km of riverbed will be dredged.

With regard to char land development, a total of 140,580 hectares of char land will be reclaimed and developed for the resettlement of local populations. Furthermore, 17,540 hectares of land will be developed as EZs to attract foreign and domestic investment in a wide range of industrial and service sector enterprises. It is anticipated that the development of char lands will be completed by 2040.

16.1.3 Investment Costs

The investment costs of riverbank protection works, flood embankments, roads, dredging and low spurs have been estimated on a kilometer basis at 2019 market rates. The costs of char land reclamation and development were estimated at BDT 0.15 million per hectare for rural settlements and BDT 11 million per hectare for EZs. The EZ development costs included public infrastructure such as roads, electricity, water supply and telecommunications necessary for the establishment of modern facilities.

The total investment costs of the RSP are estimated at BDT 617.28 billion (USD 7.26 billion) – see Table 8. The EZ development costs of BDT 192.94 billion (USD 2.27 billion) accounted for the highest proportion of the total investment (31.2%). The riverbank protection costs of BDT 158.87 million (USD 1.87 million) comprised 25.7% of total costs and flood embankment costs accounted for 14.7% of total costs. Dredging and road development also represent a significant proportion of investment costs at 12.5% and 8.3% respectively.

Table 8: Investment costs for RSP, 2015 to 2050 (BDT M).

Year	Riverbank Protec-tion	Flood Mitiga-tion	Road Dev't	Dredging	Low Spurs	Char Development		Total
						Rural Settlement	Economic Zones	
2015 – 2020	12,128	9,116	6,078	0	0	1,377	0	28,699
2020 – 2025	57,344	20,294	9,563	19,380	0	4,650	5,940	117,171
2025 – 2030	27,657	9,053	6,035	30,753	5,100	4,125	55,000	137,723
2030 – 2035	61,736	16,787	5,525	18,437	6,375	3,210	66,000	178,070
2035 – 2040	0	14,025	9,350	8,619	13,770	7,725	66,000	119,489
2040 - 2045	0	21,675	14,450	0	0	0	0	36,125
2045 - 2050	0	0	0	0	0	0	0	0
Total Cost (BDT M)	**158,865**	**90,950**	**51,000**	**77,189**	**25,245**	**21,087**	**192,940**	**617,276**
Total Cost (USD M)	**1,869**	**1,070**	**600**	**908**	**297**	**248**	**2,269**	**7,261**
% of Total	**25.7%**	**14.7%**	**8.3%**	**12.5%**	**4.1%**	**3.4%**	**31.2%**	**100%**

In addition to the public investment costs given in Table 8, EZs will also require private investment in order to develop a wide range of industrial and service sector enterprises to meet the rapidly growing demand from both the domestic and export markets. At present, EZs in Bangladesh are currently attracting about USD 5.0 billion of private investment per hectare, so private investment was therefore estimated at BDT 7,450 billion (USD 87.7 billion) for the 17,540 hectares of EZs to be established under the RSP.

16.1.4 Economic Benefits of Riverbank Protection

The economic benefits resulting from the mitigation of riverbank erosion were derived from the estimated areas of mainland and char land which would be lost if riverbank protection measures were not implemented. Based on 2019 prices for agricultural, homestead, and market/commercial land, the values of land and assets which will be saved from bank erosion were estimated for mainland and char land areas within each river reach.

The estimated areas of mainland and char land protected from riverbank erosion, together with the economic value of the land and assets, are given in Table 9. By 2050, it is estimated that 20,564 hectares of land will be protected from erosion and the economic value of the land and assets is BDT 69.38 billion (USD 0.82 billion).

To reflect the increasing demand for protected land, it has also been assumed that there would be an overall increase in the value of land and assets at the rate of 2% per annum. This annual increase in land values is based on the expected expansion in settlements within the protected areas. If this increase in land values (in real terms) is included, the economic value of protected land and assets rises to BDT 179 billion (USD 2.11 billion).

Table 9: Riverbank protection: areas and economic value of assets protected by 2050.

River Reach	Area Protected from Erosion (ha)			Economic Value of Land and Assets Protected	
	Mainland	Char Land	Total	BDT M	USD M
Jamuna					
Reach 1	1,965	3,008	4,973	40,387	475.1
Reach 2	45	2,796	2,841	11,517	135.5
Reach 3	790	1,271	2,062	17,766	209.1
Padma					
Reach 4	4,753	4,602	9,355	98,925	1,163.8
Reach 5	397	937	1,334	10,392	122.2
Total	7,950	12,614	20,564	178,988	2,105.7

16.1.5 Economic Benefits of Flood Mitigation

Based on the results of the flood modelling study over different time periods, the areas protected from floods (following the construction of embankments at various stages of the phased development) were determined (Table 10). By 2045, it is estimated that an area of over 700,000 hectares would benefit from flood mitigation along the five river reaches. For each time period, the annual economic benefits of constructing flood embankments were determined on the basis of benefitted area, number and value of the main assets located within the vulnerable areas to be protected from flooding, and probability of damage under various flood scenarios.

Based on the above analysis, the annual economic benefits of flood mitigation were estimated to total BDT 15.95 billion by 2045 (Table 10).

In addition to mitigating flood damage, increases in crop production are also likely to be gained from reduced flooding due to a change in cropping pattern and increase in crop productivity. The incremental annual benefits from crop production were estimated at BDT 5,184 million in 2045. Furthermore, it is also anticipated that a reduction in flooding would facilitate an increase in culture fish production and the incremental annual benefits from fish production were estimated at BDT 1,234 million in 2045.

16.1.6 Economic Benefits of Char Land Development

In this assessment, it has been assumed that a total of 158,120 hectares of char land will be reclaimed and developed, comprising 140,580 hectares for agricultural development and rural settlement, and 17,540 hectares for the establishment of EZs.

Table 10: Flood mitigation: areas and annual economic net benefits, 2015 to 2045.

Time Period	Embank -ment (km)	Area Benefiting from Flood Mitigation (ha)	Annual Flood Mitigation Benefits (BDT M)	Annual Incremental Agricultural Benefits (BDT M)	Annual Incremental Fisheries Benefits (BDT M)	Annual Flood Mitigation & Agric/ Fisheries Benefits (BDT M)
2015 - 2025	185	168,913	2,138	1,242	296	**3,675**
2025 - 2030	70	94,419	2,430	694	165	**3,290**
2030 - 2035	65	83,272	2,143	612	146	**2,910**
2035 - 2040	110	140,921	3,627	1,036	247	**4,910**
2040 - 2045	170	217,787	5,606	1,601	381	**7,588**
Total	600	705,312	15,945	5,184	1,234	**22,363**

With regard to rural development, land use plans were derived for each area of char land. Estimates of the annual net economic benefits which are likely to be derived from agricultural and forestry development as well as the establishment of rural settlements were then determined. The overall net economic benefits from rural development were estimated at BDT 35,458 million per annum by 2040 (Table 11).

River stabilization and char land development will also provide an opportunity to develop EZs in key locations. In addition to the EZs already planned at Sirajganj (420 ha) and Old Aricha Ghat (120 ha), it is also proposed that EZs are established at Dohar (6,000 ha), Faridpur (8,000 ha), and Munshigang (3,000 ha). Based on the performance of existing EZs, it was estimated that annual net economic benefits of the proposed EZs would total BDT 1,870 billion in 2040.

Table 11: Char land development: areas and annual net economic benefits by 2040.

River Reach	Area of Char Land Development (ha)			Annual Net Economic Benefits from Char Land Development (BDT M)		
	Rural Settlements	Economic Zones	Total	Rural Settlements	Economic Zones	Total
Jamuna						
Reach 1	50,500		50,500	13,864		13,846
Reach 2	27,280	420	27,700	5,776	44,767	53,543
Reach 3	37,700	120	37,820	8,102	12,791	20,766
Padma						
Reach 4	9,100	14,000	23,100	3,013	1,492,249	1,498,789
Reach 5	16,000	3,000	19,000	4,890	319,768	330,459
Total	140,580	17,540	158,120	35,627	1,869,575	1,905,202

16.1.7 Economic Benefits of Navigation and Road Transport

Dredging and the revetment works are expected to lead to the deepening of channels to facilitate navigation along the Jamuna and Padma Rivers. In the estimation of the annual net economic benefits from improved navigation, it has been assumed that the proposed dredging will enable larger vessels (i.e. greater than 200 tonnes) to utilize the routes during the dry season and so facilitate an increase in annual cargo volumes. Based on larger cargo volumes, it is estimated that the annual net economic benefits from dredging will be BDT 12,710 million by 2045 (Table 12).

With respect to the economic benefits of constructing 600 km of embankment roads, a vehicle operating costs (VOC) approach was adopted. This approach is based on the estimated reduction in VOCs of motorized and non-motorized vehicles following the implementation of a road project. The results of this analysis indicated that the annual net economic benefits from the construction of an embankment road will be BDT 6,726 million by 2045 (Table 12), of which about 75% would be generated by existing traffic and 25% would be obtained from new traffic.

Table 12: Navigation and roads: length of works and annual net economic benefits by 2045.

River Reach	Road Transport		Navigation	
	Length of Works (km)	Annual Net Economic Benefits (BDT M)	Length of Works (km)	Annual Net Economic Benefits (BDT M)
Jamuna				
Reach 1	170	1,530	94	5,946
Reach 2	70	756	36	2,364
Reach 3	185	1,699	40	2,853
Padma				
Reach 4	105	1,692	28	1,547
Reach 5	70	840	0	0
Total	600	6,517	198	12,710

16.1.8 Overall Net Economic Benefits and Contribution to National Economy

The annual net economic benefits from flood mitigation, char land development, improved navigation and road transport are combined together in Table 13 and it can be seen that annual net economic benefits will amount to BDT 1,947 billion (USD 22.9 billion) in 2050. It is also clearly evident that EZs make, by far, the largest contribution to annual net economic benefits accounting for 98% of overall net economic benefits.

Table 13: RSP: annual net economic benefits of proposed interventions in 2050.

Intervention	Annual Net Economic Benefits		
	BDT M	USD M	% of total
Flood Mitigation	**22,363**	**263**	**1.1%**
Reduced Damage	*15,945*	*188*	*0.8%*
Incremental Agriculture	*6,418*	*76*	*0.3%*
Char Land development	**1,905,202**	**22,414**	**97.9%**
Rural Settlements	*35,627*	*419*	*1.8%*
Economic Zones	*1,869,575*	*21,995*	*96.0%*
Road Transport	**6,517**	**76**	**0.3%**
Navigation	**12,710**	**150**	**0.6%**
Total	**1,952,386**	**22,902**	**100%**

In 2019, the GDP of Bangladesh was estimated at BDT 26,690 billion (USD 314 billion), so the economic value provided by the RSP, particularly the EZ component, will make a significant contribution to economic growth over the next 30 years. It is also important to note that the rural settlement and flood mitigation components will also provide increasing employment opportunities and reduce poverty in the rural areas located along the river corridor.

In addition, the RSP will protect land and assets valued at BDT 69.38 billion (USD 0.82 billion) from riverbank erosion over a 30year period.

16.2 Environmental and Social Impacts of the Reference Project

At this early stage of project planning and implementation, social and environmental impact assessment emphasizes the identification of potentially significant impacts ("scoping"). Additional environmental and social impact investigations and the development of impact management measures will be undertaken during each future stage of planning and implementation, with the ultimate objective of achieving project outcomes that are environmentally and socially acceptable.

The information presented here summarizes the impact assessment of the RSP Reference Project (see Section 3.6 and Chapter 15) undertaken by the SESA team (Chapter 5, SESA, April 2020). These SESA findings are tentative and preliminary and should be read as such. The focus of this summary is on potential positive and negative impacts. Mitigation and management measures are mentioned only briefly and as needed.

Impacts are assessed relative to a future-without-project baseline. This baseline is subject to very large uncertainties due to (i) significant natural annual and interannual stochastic variability in flows, sediment loads, and river planform; (ii) very limited long-term historical observations available; and (iii) significant uncertainty about non-RSP anthropogenic processes and their future environmental impacts.

Impacts can be positive or negative; fully, partially, or not mitigable; short- or long-term; immediate or delayed; local or remote; intentional or unintended / accidental; project-on-environment or environment-on-project; "normal" or catastrophic; can occur during pre-construction, construction, operation, and/or decommissioning; and can act in isolation or cumulatively in concert with the impacts of other natural and anthropogenic trends and events.

16.2.1 Potential Construction-Phase Impacts of Engineering Works and Dredging

The main impacts include:

- Pollution from construction and dredging air/water emissions and solid waste
- Energy used and carbon dioxide emitted by construction and dredging activities
- Disruption of transportation at construction sites
- Interruption of land use at sites occupied temporarily for construction and dredging operations
- Impacts on aquatic biota of increased suspended sediment during and after dredging
- Impacts of dredge spoil on and near spoil disposal sites
- Social and environmental impacts of labor force movement, presence, etc.

16.2.2 Impacts of River Engineering Works and Dredging for Main River Erosion Control and River Planform Stabilization

The main potential positive impacts include:

- Establishment of a stabilized Flood Corridor, approximately six to eight kilometers wide for the Jamuna, and eight to ten kilometers wide for the Padma, composed of a Floodplain zone along both banks, and an Alluvial Corridor containing a permanent year-round river channel called the Low Flow Corridor (Figure 17)
- Reduced riverbank erosion, and decreased erosion in the Floodplain zone generally
- Expanded deeper river habitats, utilized by some river fish species and the endangered Ganges River dolphin Platanista gangetica
- Demarcation of environmentally-protected areas at stabilized land-water boundaries.

Main potential negative impacts include:

- All char land located within the Low Flow Corridor will be extirpated. All inhabitants and users of these mostly younger (one to two years old), less-heavily settled and exploited chars will be displaced as these areas convert to open water. Post-project economic activity in the Low Flow Corridor footprint will be river-based e.g. capture fishing and navigation
- Converting a large, braiding/meandering river to a stable Flood Corridor configuration will significantly alter wetland habitats. The historic widening process mainly increased land and sandy areas. Reversing this process will shrink the area of temporary pools and waters used by mussels, crustaceans, worm, and other aquatic benthic fauna, plus some fish species; and the area of sand/gravel islands used for breeding by some bird species e.g. river tern, black-bellied tern, little tern
- Geobag decommissioning impacts. Not well understood, will be studied, expected to be benign
- Construction-phase impacts of engineering works and dredging (listed above).

16.2.3 Impacts of Stabilizing Char Lands and Raising Char Land Levels

The Reference Project envisages stabilization of 154,000 ha of char land in six areas on the right bank, seven on the left, plus one island; of which, ten areas along the Jamuna comprise 112,000 ha and four along the Padma comprise 42,000 ha (Figure 18). Most of the area to be stabilized is char land that supports settlements and agriculture. Younger chars predominate in Reach 1 (upper Jamuna) and older chars in Reaches 2 and 3 (middle and lower Jamuna).

Stabilization will be achieved by pilot dredging to re-align flows and construction of engineering works to promote sediment deposition; and by dumping of dredged sand. In agricultural areas, a fertile top layer will be (re-)established or enhanced by planting reeds to trap floodwater suspended sediment. The stabilization timeframe is uncertain due to inadequate data on the amount of river sediment that can diverted to this activity without adverse effects.

Main potential positive impacts of dredge spoil dumping and reed plantation include:

- Conversion of low-lying, fragmented char areas to larger highland parcels

Main potential negative impacts include:

- Temporary or permanent displacement of inhabitants, users, and biodiversity of lands where dredge spoil is dumped and reeds planted
- Construction-phase impacts of dredging (listed above)

16.2.4 Impacts of Flood Embankments and Associated Structures

The Reference Project envisages a Flood Corridor with left and right multi-use embankments, set back from protected riverbanks by 50 to 300 m and from unprotected riverbanks to up to several kilometers, protecting countryside areas from flooding up to the 500-year return period. Embankments will be provided with appropriate water control structures for drainage, flushing, navigation, fish passage, etc.

Between the embankments will be a Flood Corridor consisting of (i) a Floodplain zone that accommodates river flood flows in the wet season, and supports grazing and seasonal cropping in the dry season, and (ii) an Alluvial Corridor that accommodates natural river sedimentation processes (Fig. 16). Ecologically, the Flood Corridor footprint will continue to be occupied by a biodiverse and dynamic interconnected system of permanent and seasonal wetlands, while at the same supporting a range of human uses (seasonal cropping, grazing, fishing, navigation, etc.).

The confinement effects of the left and right embankments will cause several impacts to the Flood Corridor. Confinement is expected to:

- Cause Floodplain zone land levels to aggrade by 0.2 to 0.3 m for a four to eight kilometer Flood Corridor width
- Increase maximum flood levels at higher flow rates (e.g. 45,000 m^3/s bankfull discharge). The narrower the Corridor, the greater the increase in maximum flood levels: levels could increase by 0.3 m in a six kilometer-wide Corridor but only 0.1m in a wider eight kilometer Corridor
- Cause gradual, long-term riverbed level degradation in the Alluvial Corridor, including the Low Flow Corridor, and with it, lower water levels in all seasons. This could partially mitigate the confinement-related increase in maximum flood levels (see above), but it would also cause low water levels to drop. Lower low water levels have a range of negative impacts (listed below). Therefore, riverbed degradation / lower low water levels require management to within tolerable limits: -1 m appears to be tolerable, based on historical low water level variations at the Indian border; -1.5 m merits caution, and > 2 m is unacceptable. Initial estimates suggest that riverbed degradation can be limited to 0.78 m with adaptive adjustments to Flood Corridor width (i.e. to embankment setbacks) and to river length and sinuosity. Adaptive management would also be used to address potential shorter-term and/or localized variations in riverbed depth / low water level that could occur in response to engineering works, sediment load variations, etc.

Main positive impacts of flood embankments and associated structures on in flood-protected countryside areas include:

- Reduced seasonal flooding of agricultural land, aquaculture, settlements, infrastructure (etc.)
- Reduced damage to crops and property

Main negative impacts of flood embankments and associated structures include:

- More frequent and deeper flooding, in particular higher maximum flood levels in the Flood Corridor that will affect inhabitants and users of (a) chars in the Alluvial Corridor outside the Low Flow Corridor and (b) Floodplain zone chars. The increased flooding will cause some inhabitants and users to leave; those that remain will have to adjust to and cope with the new regime. Future land use will likely be dry season grazing and seasonal crop production
- Potential adverse effects of lower low water levels in the main river, including reduced flow into distributaries; accelerated scouring at river engineering works; impediments to navigation at junctions of the main river with small navigable channels; and adverse impacts at the Bangladesh-India border
- Biodiversity impacts of blocked river-floodplain aquatic connectivity at the embankments
- Declining surface water coverage, falling ground water levels, reduced water transport, and local rainfall drainage congestion in the flood-protected area
- Loss of floodplain wetland area and duration in the flood-protected area and associated adverse quantity and quality effects on biodiversity and open water fishery production
- Construction-phase impacts of engineering works (listed above)

16.2.5 Offtake Engineering Works and Distributary Dredging

Reference Project interventions to improve distributary offtake functioning include (i) shifting offtakes to outer bend ends with defined water/sediment inflow; (ii) modifying offtake geometry to discourage excess sediment entry; and (iii) providing flood barriers (rubber dams) to extreme floods; (iii) distributary restoration through (a) capital dredging, (b) protecting critical meander bends from erosion by reintroduced flow, and (c) straightening downstream distributary reaches by cutting of meanders where appropriate.

The main potential positive impacts include:

- Increased dry season and regulated flood season distributary flows
- Improved water supply / water quality to the Planning Region including Dhaka
- Improved water supply / water quality to distributary-connected wetlands
- Enhanced biodiversity of distributaries and connected wetlands

Main potential negative impacts include:

- Construction-phase impacts of engineering works and dredging (listed above)

16.2.6 Impacts of Navigation Dredging

Main potential positive impacts include:

- Enable reliable large-scale container traffic from the Planning Region to the Bay of Bengal

Main potential negative impacts include:

- Construction-phase impacts of dredging (listed above)

16.2.7 Knock-On Impacts of Engineering Works and Dredging on Land-Based Economic Activities

Main potential positive impacts include:

- Accelerated economic development and social improvement through enhanced public and private investment opportunities in a more secure environment
- Availability of newly-stabilized highland parcels to meet various policy goals, including: industrial development; poverty reduction; reduced inter-regional disparity; more secure livelihoods for vulnerable char and river bank populations including through redistribution of khas land to landless and poor marginal farmers; agricultural intensification and promotion of commercial farming; increased forestry to reduce timber deficit; and improved wetland protection
- Reduced disaster management costs

Main potential negative impacts include:

- Potential negative impacts of accelerated economic development include increasing pollution, increased energy use, carbon emissions etc.

16.2.8 Biodiversity Mitigation and Enhancement

Possible measures include:

- Establishment of protected areas along the Padma-Jamuna, including river fish sanctuaries and conversion of lower-biodiversity char areas to higher-biodiversity protected areas
- Placement of buoys to reduce drift net use

17 INITIATING THE RIVER STABILIZATION PLAN – THE FIRST TEN YEARS

17.1 Planning for the Future

Because of uncertainties associated with forecasting natural river processes and upstream basin developments as well as the river response to systematic stabilization, this section proposes an implementation plan for the first ten years of the investment program. Prior to completing the first five years of work, a thorough review of the river response to stabilization will be undertaken and a plan for the following five years prepared. This framework of adaptive implementation is consistent with approved Plans and Guidelines including Adaptive Delta Planning in the Bangladesh Delta Plan, 2100 (GED, 2018) and a phased or adaptive approach to riverbank protection in the Guideline for Riverbank Protection (BRTC, 2010). Segmenting implementation into five year planning periods providing several advantages. Firstly, the planning period conforms to the Government’s Five Year Plan periods and entails the preparation of specific targets. Secondly, multi-year implementation contracts provide sufficient time to adapt the work to the immediate river response. Thirdly, five year periods provide adequate time for data collection and facilitate further knowledge-based development. Improved knowledge of river processes and response to the new work during the previous period then supports adaptive planning of subsequent five year investments.

Commencing work in Reaches 1 and 2 is not recommended because these reaches are less stable with a much less defined channel pattern. However, there may be a need for emergency interventions to deal with riverbank erosion at critical locations within these reaches. Examples of emergency interventions could include works at sites where there are large settlements or where important flood embankment lines come under threat. Commencing work on Reach 5, located downstream of the Padma Bridge, is also not recommended at this time. The river morphology upstream of the bridge crossing is currently nearing the end of a periodic change; it is not clear when the river will switch to a different pattern and, when it does, how this reach will be impacted.

During the initial ten years, systematic river stabilization will focus on Reaches 3 and the upstream half of Reach 4 including transitioning into the Ganges. These two reaches have a river pattern that is close to the desired pattern. Stabilizing the river here is achievable and will develop an understanding and skillset for the more difficult work in the upstream reaches.

The initial work aims to realize a number of opportunities:

1. Within Reaches 3 and 4 it is possible to recover large areas of lost floodplain, particularly at Solimabad, the confluence of Jamuna and Ganges Rivers, and Faridpur.
2. Regular navigation will be re-established in an upstream direction up to Sirajganj. From Sirajganj to Assam, through Reaches 1 and 2, dry-season navigation will be provided through recurrent dredging activities.
3. Stabilizing the channel pattern will largely eliminate erosion risk to the floodplain and prevent the flood embankments from breaching. On the left bank a flood embankment will be provided between National Highway 5 and Aricha. On the right bank of the Padma River, flood embankments will connect Rajbari and Faridpur. At regular intervals sluice gates with fish passes will optimize the flow exchange with the floodplain and particularly wetlands and khals through the embankment lines.
4. Within the newly constructed Jamuna left embankment, stable offtakes will be provided to feed the three distributaries of the Dhaleswari System throughout the year. At the embankment, flood barriers will restrict the flows to pre-defined levels.
5. The Dhaleswari channel network will be re-excavated to restore reliable dry season flow to the four districts of Tangail, Manikganj, Dhaka, and Munshiganj.

Necessary features associated with this work during the first five years include developing the riverbank protection in line with risk-based design considerations, piloting the best method for channel closures and vertical build-up of recovered char land to floodplain level, conducting social surveys on the implications of the initial stabilization works, and laying the foundation for systematic environmental monitoring and establishing mitigation measures to countermand identified negative impacts.

17.2 Knowledge-based Developments

Systematic data collection is necessary to further a detailed understanding of prevailing river processes. The main impediment for planning is the lack of systematic reliable sediment data since the mid-1990s when the River Survey Project, FAP 24 ended (Delft Hydraulics and DHI, 1996). This knowledge gap will be restored through systematic measurements along the Jamuna and Padma Rivers starting in Reaches 3 and 4. The measurements will help establish year-round stage-discharge relations for water and sediment flow. This will require additional dedicated survey vessels equipped with latest technology. Annual flood season bathymetric surveys and float tracking will complement the data collection. Data will be incorporated into the existing river survey data base operated by the BWDB Design Office. From the middle of the first Five Year Plan period, the survey work will be extended beyond Reaches 3 and 4. This information will be fundamental for the planning of major interventions in Reaches 1, 2, and 5 during the second Five Year Plan period.

The annual erosion prediction developed by the Center for Environmental and Geographic Information Services (CEGIS) in the early 2000s (EGIS, 2002; CEGIS, 2005) and the long-term prediction (for example CEGIS, 2007; CEGIS, 2018) will continue providing decision support for ascertaining where riverbank erosion counter measures are needed, particularly in Reaches 1, 2 and 5.

Satellite-based erosion prediction will be further integrated with large-scale numerical modelling (for example Supplementary Annex C3). The numerical models will be updated and expanded annually with systematic survey data, thereby improving the reliability of the models.

This combination of tools and an ever larger data set will increase accuracy in predicting future river patterns, flow distribution over channels, bank lines at risk of erosion, potential impacts of future work on the channel patterns, bed erosion, and scour along protected work.

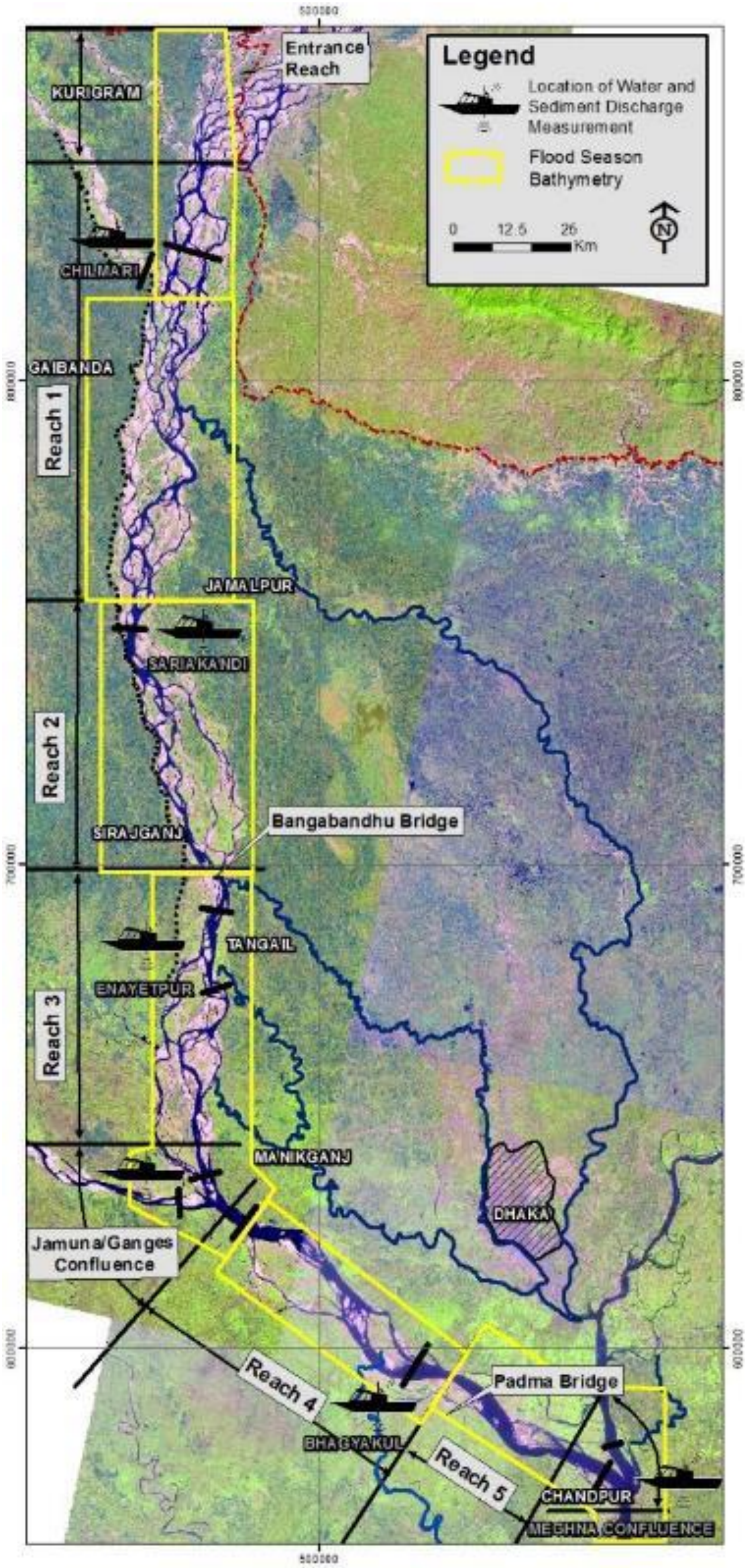


Figure 22: Main river survey stations and large-scale surveys (ISPMC).

17.3 Proposed Works in Reaches 3 and 4

Systematic interventions over the coming years can prevent major changes in Reach 3. The capital pilot dredging project carried out in 2012 has destabilized what was a stable channel downstream of Jamuna bridge crossing. The changes have started affecting the bifurcation at Enayetpur and will migrate downstream over the next several years. The proposed work is an attempt to provide basic stability to the Lower Jamuna River (Figure 23). It is comprised of 85 km of riverbank protection in strategic locations to provide the backbone for stability, the closure of a 15 km long eroding bank line channel at Solimabad, a 67 km long new left embankment, and three defined offtakes of the Dhaleswari river system with subsequent restoration of the dry season flow. Table 14 provides an overview of the proposed type of river training works, and Table 15 shows the work that would be prioritized for implementation during the 8th Five Year Plan period (identified as priority 1) and work that would be prioritized for implementation during the 9th Five Year Plan period (priority 2). The work programs would consist of an average of less than 10 km of dredged revetment and embankment construction per year, which is well within the locally available construction capacity.

Table 14: Suggested design standards for Reach 3 interventions.

<table>
<tr><th>Name</th><th>Details</th><th>Initial Volume (m^3/m)</th><th>Adaptation works</th></tr>
<tr><td>Type 1-10</td><td>Dredging of river slope to 1V:6H to a depth of 10 m below low water level. Coverage with 4 layers of geobags and provision of apron with 40 m width.</td><td>about 67</td><td rowspan="3">Strengthening of launched slope with 2 layers and provision of new apron with 4 layers until design scour is reached.</td></tr>
<tr><td>Type 1-15</td><td>Dredging of river slope to 1V:6H to a depth of 15 m below low water level. Coverage with 4 layers of geobags and provision of apron with 40 m width.</td><td>about 88</td></tr>
<tr><td>Type 2</td><td>Dumping of 4 layers of geobags on existing river slope and provision of 40 m apron.</td><td>about 40</td></tr>
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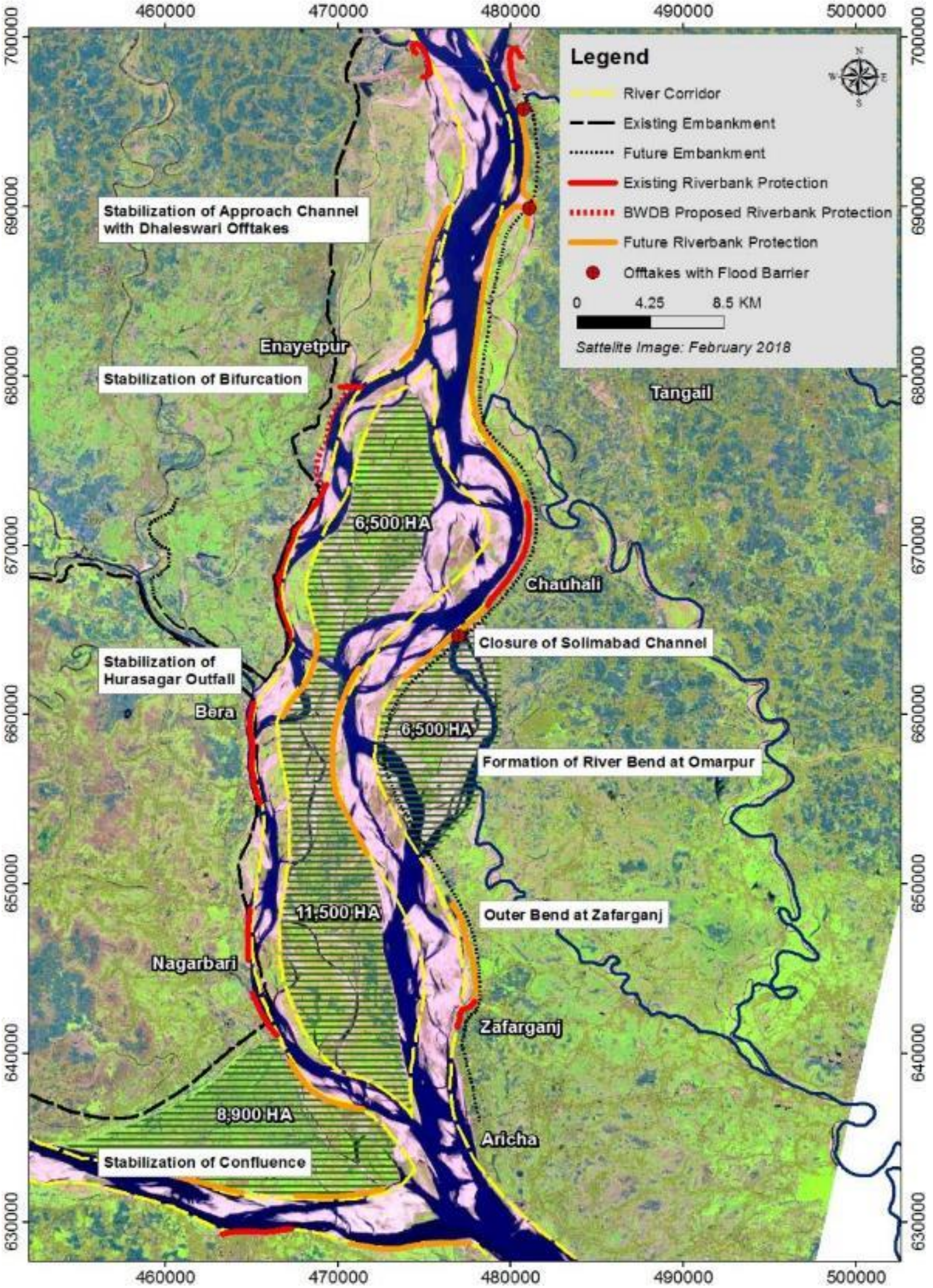

Figure 23: Work locations in Reach 3 (ISPMC).

Table 15: Summary work for Reach 3 during the coming decade.

Item	Unit	Quantity	Details (see Table 14)	Priority
River Training Works				
Approach channel stabilization on both banks	km	15	Type 1-15	1
Stabilization of bifurcation	km km	15 5	Type 1-15 Type 1-10	1 2
Closure of Solimabad channel	M m^3 km	30 6	Dredging Type 1-15	1 1
Stabilization of Hurashagar outfall	km	7	Type 1-15	1
Formation of riverbend at Omarpur	km	10	Type 1-15	2
Riverbank protection at Zionpur	km	6	Type 2	2
Stabilization of confluence	km	10	Type 1-15	2
Adaptation works	km	40	In each Plan period	1 and 2
Char Land Recovery				
Solimabad	ha	8,000	Including raising	1
Confluence	ha	9,500	Partial raising	2
Embankments				
Aricha to Dhaleswari	km	47	15 km over reclaimed land	1
Dhaleswari to Tangail	km	20		2
Distributary Stabilization and Restoration				
Ghior Khal	No	1	Offtake with flood barrier and channel restoration	1
Dhaleswari	No	1		2
Pungli	No	1		2

The river morphology in Reach 4 is associated with higher uncertainties than those of Reach 3. The downstream half of this section alternates between meandering and anabranched planform. The approximately 25-year period of meandering is coming to an end and it is not clear how rapidly the Padma will develop into a straight channel. This straight channel flowing along the left (northern) bank is the less preferred flow path and will require around 25 years to return to fully meandering. As a result, the work approach in this reach has to be highly adaptive and consider two possibilities:

1. **Higher risk alternative:** Prevent the formation of the straight channel along the northern bank. This would require substantial dredging and major land acquisition on Char Janajat. While at present this char is naturally eroding, upstream work might increase the rate of erosion and consequently warrants compensation for any additionally eroded land.
2. **Lower risk alternative:** Accept the formation of a straight channel and wait for 25 to 30 years before finally stabilizing this reach. The disadvantages are: potential uncertainty related to annual navigation conditions; the Arial Khan offtake might change its location resulting in changing inflows; and floodplain development on the right (south) bank could be delayed because distributary channels included in the Padma Bridge approach road might be blocked and won't provide environmental flows. The advantages of this approach are: it avoids a substantial investment into a high-risk channel closure; it promotes a natural river pattern in the area of the Padma bridge and avoids the liability that could be associated with causing substantial changes to the planform; and a fixed meandering and therefore longer channel path could be used in future to compensate for the degradation that could occur as a result of stabilizing the upper reach.

Given the uncertainties, the work in Reach 4 is structured in a modular way (Figure 24). The fixed work focusses on the upper half of this reach, providing substantial opportunities:

- The recovered char land at Harirampur will be protected through a flood embankment connecting Harirampur with Dohar and allowing the development of this area;
- Riverbank protection works will stabilize the right bank from Rajbari at the Ganges River to downstream of Faridpur;
- An estimated 19,000 ha of floodplain land at Faridpur will be recovered and developed; and
- Consistent flood protection will be provided between Rajbari and Faridpur as well as Harirampur and Dohar.

Table 16: Summary work for Reach 4 during the coming decade.

Item	Unit	Quantity	Details (see Table 14)	Priority
River Training Works				
Ganges right bank	km	10	Type 1-10	main
Faridpur right bank	km	15	Type 1-15	main
Adaptation works	km	30	In each Plan period	main
Optional Bagyakul channel closure	million m^3	50	Pilot closure	
Char Land Recovery				
Faridpur	ha	19,000	Including raising	main
Optional Bagyakul	ha	15,000	Partial raising	
Embankments				
Harirampur to Dohar	km	17	8 km over reclaimed land	main
Rajbari to Faridpur	km	40		
Distributary Stabilization and Restoration				
Faridpur channel	No	1	Offtake with flood barrier	main

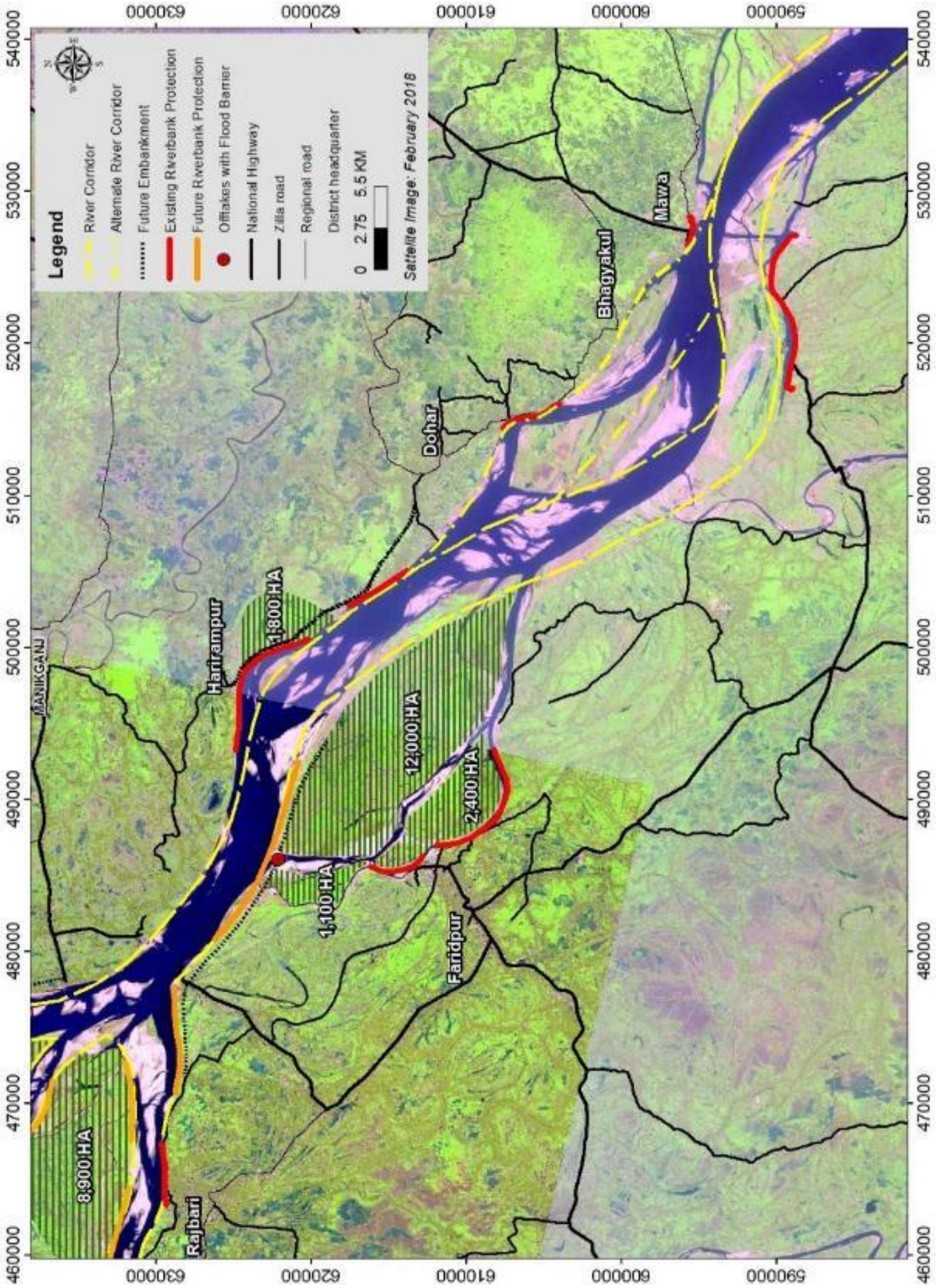

Figure 24: Work locations in Reach 4 (ISPMC).

17.4 Implementation Considerations

17.4.1 River Training Techniques – Piloting Innovative Technologies

River stabilization of a world-wide unique river requires a careful approach to avoid costly failures. Adaptive Delta Management following a “no-regret” approach to avoid “lock-in” situations is largely based on “learning by doing” (GED, 2018). In this context pilot works play an important role, the more so since several river training technologies require further development. Examples of pilot projects and potential use of innovative technologies are listed below.

1. Riverbank protection along a stabilized river corridor with progressively increasing investments requires work that can be adapted to the investment level on the floodplain. However, there are limitations. A generally higher level of design incorporates two fundamental elements, both achieved through dredging technology: the flattening of the underwater slopes as well as the placement of the toe protection apron at deeper levels. Dredging of flatter slopes is especially indicated alongside the weak soils of the left bank and around chars. This technology will be introduced and systematically developed in Reach 3 during the first Five Year Plan period. The key driver will be the ongoing FRERMIP project (ADB, 2014).
2. The recovery of lost floodplain land depends on the development of efficient channel closure mechanisms. During a first phase the sediment at the bifurcation will be redistributed through dredging to close unwanted bank line channels. Subsequently, the vertical buildup of the aggrading land to floodplain level will be encouraged. This will be achieved through bio-engineering measures, harvesting suspended sediment to form a fertile top layer.
3. A stabilized river planform will allow the development of stable offtake locations and subsequent revival of dry season flows. The demand to restore dry season flow will require the development of efficient dredging technologies that avoid deposition of sediment on the floodplain (for example agitation dredging). The long-term development of the floodplain will depend on flood barriers at the offtake to restrict the inflow for example to a 10-year flood level and avoid that the enlarged distributary floods the generally flood protected areas. Piloting this approach is planned for the small and least important Ghior Khal or Old Dhaleswari under FRERMIP (ADB, 2014).
4. The development of navigable channels is much encouraged through the self-dredging alongside long revetments. However, at the transition to unprotected reaches, specialized structures will be required to guide the flow to the opposite meandering bend. Low spurs, which provide a high horizontal permeability (overtopping) during flood flows, are typically used. Bangladesh has experience with vertically permeable structures consisting of rows of piles (Jamuna Test Works Consultants, 2001). Both types of works will be pilot tested towards the beginning of the second Five Year Plan period for systematic application during the following decades.

17.4.2 Environmental and Social Aspects during the Transition towards a Stabilized River

Environmental safeguards will be part of finalizing the work plans. What follows are considerations that could be part of these safeguards.

In parallel with the development of river training techniques, environmental enhancement measures will be piloted. While the systematic plantation of reeds for capturing the suspended load and building up chars is a technology serving this purpose, additional developments pertaining to the increase in fish population are planned. Along the riverbank, buoys will be placed in different arrangements not only to guide navigation, but also to prevent drift net fishing and provide systematically placed, undisturbed habitats in areas with deeper channels. Embankments will be equipped with sluice gates having fish passes to develop optimized solutions for fish migration to and from the floodplains. The offtake geometry of distributaries will encourage year-round fish movement back into the distributary courses and will be piloted for the Ghior Khal (Old Dhaleswari) before being implemented for the main Dhaleswari course. In parallel with the piloting of individual elements, systematic studies of the riverine environment will continue. These studies will not only help to establish a stronger baseline of the existing situation, they also help to develop suitable mitigation measures resulting from river stabilization impacts. It is necessary to start these investigations from the first year, to develop a sufficiently broad data base and understanding of the transition to stabilized river before the more problematic Reaches 1, 2, and 5 are addressed.

The large central char in Reach 3 will play a pivotal role during the process of converting unstable chars to more stable ones. Char dwellers overwhelmingly prefer an erosion-free environment, which also means legal rights to their land holdings need to be confirmed. After stabilization, land previously eroded and now in a main channel will not likely re-emerge. Compensation mechanisms and solutions that serve all people displaced by the stabilized river boundaries will need to be put in place. The development of attached chars, which was formerly eroded floodplain, provides an opportunity to restore the livelihoods of many people affected by erosion. Specialist studies will be needed to identify the best way forward and to advise the Government of how best to address the issues before more systematic land recovery is started in the other reaches.

17.4.3 Communication Strategy and Capacity Development

River stabilization and its potential consequences requires regular and clear communication. For the broader public, there is the need not only to communicate the plan itself, but also the uncertainties and risks. In this way expectations can be managed as the work will not be free of failures or perceived failures. The communication of the adaptive approach will provide additional assurance that once work has commenced it will not be left alone and continue as part of a larger scheme over time. On a different level, local stakeholders need to be provided with knowledge as to their rights and obligations. This could be fundamental to smooth the transition from living in a physically unstable environment to living in a physically stable, but socially more dynamic world. To address these needs, a communication and training strategy will need to be part of the detailed implementation arrangements.

17.5 Implementation Arrangements

17.5.1 Flexible Implementation - Processing and Financing

The RSP requires flexible funding and flexible implementation arrangements. Unpredictable river changes require flexibility on a number of levels:

1. **Opportunity-driven implementation.** This requires immediate action when river conditions are favourable. These conditions typically arise after higher floods and provide an opportunity to follow an optimal river alignment. Not taking advantage of these opportunities can substantially increase the cost.
2. **Adjustments prior to implementation.** The low predictability of the river does not allow to determine the exact work length and location years ahead of implementation. Consequently, the worksite needs to be adjusted immediately prior to implementation to match the erosive patterns and plan requirements.

3. **Adaptation works after river attack.** Typically within the first few years, new works will require adaptation measures such as strengthening launched aprons under water. It is not possible in advance to determine the exact location and length of this adaptation work. However, over river reaches and periods of time the requirements average out.
4. **Unpredictable river response.** The changing hydro-morphology often surprises designers when it comes to erosion patterns along riverbank protection works. Not only new, but also long established works might require sudden adaption works, or urgent mitigation measures might become necessary in river reaches beyond the area being worked on.

All of this speaks to the need for flexible implementation arrangements. These would include flexible Development Project Proformas with block allocation of funds for five years, combined with on-call work contracts for work in a river reach also for four to five year periods.

17.5.2 Bangladesh Water Development Board

The BWDB has set up the post of Chief Engineer River Management with responsibility for stabilizing river reaches. Flexible implementation along with developing new technologies requires a specialized planning and design office. It also requires close coordination between design and construction during implementation. To ensure feedback to the design and implementation process, a specialist monitoring, evaluation, adaptation, and maintenance (MEAM) wing is needed. Ideally, all of these offices would be located under the Chief Engineer River Management, and would be tasked with initiating the work on Reaches 3 and 4. The ongoing work associated with passively reacting to riverbank erosion in the other reaches as well as the responsibility for flood protection embankments will remain under the Zonal Chief Engineers.

The BWDB, through the Chief Engineer River Management, will closely coordinate the work with involved parties and communicate the activities to a broader public. High level coordination with the Delta Wing of the Planning Commission will ensure that national interests are served.

17.5.3 Land Use Planning

Recovered char land requires a transparent land use planning process. This is a challenge. Practically all land has been owned by private parties at one point, even though it turned into khas or Government land after erosion. The conversion into floodplain involves substantial expenditure and effort, and its value is best captured through highly productive use. The combination of multiple development interests requires the involvement of a senior level of government which could include land, industry, agriculture, and planning ministries. Given the time it takes to raise low-lying char land to the level of the floodplain (5 to 10 years), there will be time to establish these plans.

17.5.4 Funding

The cost estimates are based on the BWDB's schedule of rates or engineering estimates when it comes to dredging cost. The investment cost for the work in Reaches 3 and 4 over a period of 10 years are estimated to around BDT 72.5 billion or USD 840 million (Table 17). Typically, an additional 30% of this amount would be required for land acquisition, resettlement, other development works, knowledge-base development, and project management. Out of an estimated total of BDT 95 billion or USD 1.1 billion, immediate implementation in Reach 3 and part of Reach 4 is assured through the ongoing FRERMIP project, providing overall funds of around BDT 25 – 42 billion (or USD 300 to 500 million). An added advantage of the initial FRERMIP resources is that they can be used for the planning process of the remaining works.

Table 17: Summary investment cost (numbers rounded).

Item	Reach 3		Reach 4	
Riverbank protection	85 km	USD 430 million BDT 37 billion	25 km	USD 130 million BDT 11 billion
Embankments, including regulators and road crossings, excluding land acquisition	67 km	USD 140 million BDT 12 billion	57 km	USD 120 million BDT 10.5 billion
Offtake with flood barrier	3 barriers	USD 10 million BDT 0.9 billion	1 barrier	USD 10 million BDT 1 billion
Totals		USD 580 million BDT 50 billion		USD 260 million BDT 22.5 billion

18 COMPARISON WITH OTHER PLANS

During the course of the FRERMIP project, four other river stabilization plans have been proposed:

1. Concept Paper on Managing Brahmaputra-Jamuna River System (BUET/BWDB, 2019);
2. Brahmaputra-Jamuna River Economic Corridor Development Program (IWM, 2019);
3. Planning for Flood Management in Bangladesh (Ganges and Brahmaputra Basin), Yellow River Engineering Consulting (2019); and
4. Feasibility Study of Capital Dredging and Sustainable River Management in Bangladesh, (BWDB, September 2015).

Table 18 summarizes the similarities and differences between the various plans. The principle features of each plan are reviewed in the following sections.

18.1 BUET-BWDB Conceptual Paper

The goal of the plan was to reduce hazards related to flooding and erosion and enhancing socio-economic-environmental benefits along the Jamuna River. The vision of the study is that the river will be a free-flowing river within its braided corridor, it will not erode or flood outside its corridor and it will provide optimized ecological and sociological services. The approach to managing braided river systems was partially based on the work by Piégay et al (2006), which focused on smaller mountain (gravel-bed) rivers. The concept paper did not differentiate between the highly braided reaches of the upper Jamuna River and the more anabranched reach downstream of Bangabandhu Bridge. Also, by restricting the historical analysis to the last 25 years, it concluded that the only stable planform was the recent braided one, without appreciating alternative forms observed historically.

The study concluded that revetments were more efficient than spur dikes and consequently proposed them for systematic riverbank protection. Protecting the outside boundary of the braided corridor will result in 200% of the river length being protected (two banks on each side). Additional bank protection was proposed on some mid-channel chars. This layout of protection results in 716 km of bank revetment for approximately 225 km of river, or more than 300% of its total length. The study did not estimate costs for the protection. Experience on the Yellow River has shown that using other methods, such as bend control, could substantially reduce the required protected length. For example, it was demonstrated that some 30 to 60% of one bank requires protection if a meandering or curved alignment is followed.

Another major component of the proposed work is based on the concept of “intelligent dredging”. The first element of intelligent dredging pertains to excavating a single or anabranched river alignment through the existing braided corridor. The Concept Paper suggests a 450 km long channel. The dredging would straighten the channel and would achieve a planform similar to some previous concepts (CBJET, 1991; Halcrow, 1994; Feasibility Study of Capital Dredging and Sustainable River Management in Bangladesh - FSCD & SRMB, September 2015). The volume of material to be moved is estimated to be 100 million cubic meters. Moving this volume of material would require 5 of the largest dredgers available today working continuously for 5 years. The total long-term dredging volume required could exceed 1 billion cubic meters. Dredging around 1 billion cubic meters would require decades and dredging of the initial channel would have little impact if the maintenance dredging was not carried out.

The second aspect of intelligent dredging pertains to the filling of reclaimed land. The Concept Paper proposes around 3.5 m fill on reclaimed land to raise it above 20-year flood level. Raising of low-lying land with dredged sand will lead to low-fertility land not suitable for agriculture. Other usability would depend on additional investments for land development and access infrastructure. The more serious problem is that this activity would consume the entirety of the currently available sand load of the river for a period of 50 to 100 years.

The Concept Paper does not provide cost, implementation schedule, or an estimate of benefits. This makes it difficult to assess the implementation constraints as well as the social impacts or economic feasibility. Also, some remote sensing tools required to guide the dredging operations are still under development. Therefore, although this approach is visionary, it may not be feasible under the present technology.

18.2 Brahmaputra-Jamuna River Economic Corridor

The Institute of Water Modelling (IWM) submitted the Brahmaputra-Jamuna River Economic Corridor Development Plan in November 2019 (IWM, 2019). The objective of the study was “*to provide a technical foundation for developing a framework of investment for the Brahmaputra-Jamuna reach*”. More specifically, the objectives of the study were to:

1. Improve the navigation route, emphasizing establishment of an Indian protocol route for trans-national waterway.
2. Reclaim land through stabilizing banks, chars and navigation channels under strategic adaptive river training works.
3. Gradually stabilize the whole Jamuna River course and rationally narrow down the average width of the braiding river valley between 5 and 8 km within the reach between Noonkahawa and Aricha.

The study is restricted to the Jamuna River and does not include work along the Padma River. The study concluded that stabilizing the entire Brahmaputra-Jamuna River is not feasible in the short and medium term. It was indicated that the overall tendencies to river-widening have slowed down but not in equilibrium to fully justify expensive river training works. However, the majority of the river

Table 18: Comparison of river stabilization plans.

	FRERMIP	BUET-BWDB
Planning Time Frame	2100 (Long-term); 2050 (medium-term)	2100
Spatial Extent	Jamuna, Padma River including major distributaries	Jamuna
Integration with Delta Plan	Compatible-time frame and adaptive planning (DAPP) approach adopted	Adaptive dredging
Plan Goals	Reduce flood risk by stabilizing main rivers, improve quantity and quality of distributary branches, improve water transport, promoting safe development of reclaimed char land	Free flowing Jamuna within braided corridor. Provide optimized ecological, socio-economic and environmental services
River stabilization strategy	Establish a stabilized corridor for conveying water and sediment to minimize future widening, promote natural restoration of former floodplain and promote long-term stability of distributary channels.	Dredging of active and developing channels aided by modelling simulations and real-time bathymetric data. Free-flowing
River Training Methods	Primarily bend control with guiding revetments	Mainly dredging, continuous protection of embankments by revetments
Stabilized channel pattern	Primarily single or two channels, meandering to anabranched pattern. Braided reach of Jamuna (R-1, R-2) retains multi-channel pattern until future conditions improve	Wide, braided corridor with set-back flood embankments protected by continuous revetments
Width of stabilized river corridor	Jamuna Flood Corridor: 6.0 to 6.5 km Jamuna Alluvial Corridor: 3 km Padma Flood Corridor: 8.0 to 10 km Padma Alluvial Corridor: 4 km	Varies 11.5 km -15 km
Land reclamation strategy	Combination of accelerating natural floodplain accretion, dredging, structural measures	3 options, total area varies from 375km2 to 644 km2
Distributary Channel Rehabilitation	Offtake control tied in to stablized main channel. Dredging distributary channels	Modified openings (not specified), recurring dredging, new embankments
Navigation Channel Improvement	Dredging along stabilized main river channels to maintain improved transport in dry season	Not described
Environmental/social impacts	SESA completed	Not described
Estimated Cost	US$ 7.26 billion (61,700 Crore BDT)	Unknown, expected to be very high due to continuous revetment, very high capital & maintenance dredging
Focus of First Ten Years	Mid-lower) Jamuna (Reach 3) + Padma	Not described
Comments		Dredging volumes are expected to be exceptionally large (up to 3.6 billion cubic meters), which is unlikely to be feasible with present technology. Impacts of sediment removals not defined.
Impacts		Simulation shows approx. 5 m degradation at Indian border (pg. 87 & Fig 4-22)

IWM	Yellow River Engineering Cons.	Capital Dredging Project
Not described	2035	15 years
Jamuna	Jamuna-Padma-Ganges	Jamuna-Padma
Not described	Not described	Not described
Stabilizing Jamuna to utilize its potential for inland transport and reclamation of char land	Establish a flood control engineering system to increase security against flooding and erosion for mainstream and tributaries.	Channelization of Jamuna and Padma River to stabilize river, improve navigation, reclaim land
River training to limit further erosion and promote reclamation of floodplain and chars	Comprehensive strengthening of embankments, riverbanks. Dredging if necessary to control deposition that threatens channel stability	Capital dredging up to 9.8 billion m3 in stabilized channel protected by revetment
Permeable groynes to protect embankments, floodplain and raised chars	Bend- node control using revetments and groynes with set-back embankments	Continuous revetment confining dredged channel
Braided	Generally follows existing flow paths with a meandering or anabranched planform	Mostly a single thread meandering channel
Varies between 5-8 km	Jamuna: 4 km main channel, 2 km branch channel Padma: 3.5km main channel, 1.5 km branch channel	4 km
Filling by dredging (up to 2 billion cubic meter)	Cultivable land increased between stabilized bank and set-back embankment	Dredged fill behind embankments
Not described	Not described	Dredging
Dredging along stabilized main river channels to maintain improved transport in dry season	Not described	Stable channel alignment maintained by dredging
Not defined		Very large
US$12.4 billion (105,000 Crore BDT)	US$ 5.59 billion (47,500 Crore BDT)	>US$ 110 billion (935,000 Crore BDT) based on annual costs over 15 years
Not described	Not described	Not described
Previous experience with permeable groynes has had limited success and been superseded by other more effective methods.		Cost based on annual average investment of US$ 7.7 billion (BDT 640 billion BDT) for 15 years
Simulations show >10 m of degradation near Indian border		

system can be sustained in a 5 to 8 km wide corridor utilizing measures that are adaptive in nature to the future uncertainties of the hydro-morphological dynamics. The modified river corridor will have a deep main channel and several secondary channels with enough capacity to convey large flood flows and enough depth to support improved navigation. The adaptive approach is consistent with the dynamic, adaptive approach (DAPP) that has been adopted in FRERMIP and the possible development pathways that have been identified.

The study proposes to use permeable groynes for the river stabilization work. Pilot-projects would be required to confirm the performance and feasibility of these measures. Prevous pilot scale testing of permeable groynes in the 1990s during the FAP program showed only limited success with this approach and other types of protection (such as guiding revetments) have generally proven more successful, in terms of reduced scour and lower susceptibility to damage. Given the limited positive experience with permeable groynes, the feasibility of this approach is not clearly demonstrated. The impacts of the structures on the riverbed profile appears to be large (based on the results from the morphodynamic modelling), particularly in the upstream reaches.

Land reclamation of chars and raising of islands is proposed by using dredge fill. This would require up to 2 billion cubic meters of dredging, which is an exceptionally large volume of work.

18.3 Yellow River Engineering Consulting River Stabilization Plan

This plan is an update and extension of the earlier feasibility studies conducted by the China-Bangladesh Joint Experts Team report (CBJET, 1991). The current plan includes the Jamuna, Padma and portions of the Ganges Rivers as well as major tributaries. The long-term planning horizon was to 2035. The overall objectives were to establish a flood control engineering system for the mainstreams and tributaries, preventing the westward migration of the Brahmaputra-Jamuna River and giving consideration to increasing the available floodplain to increase flood security.

The planned bank protection and river stabilization works were to use a combination of node control and bend control, consistent with the previous CBJET (1991) study. A combination of groynes and revetments were proposed. The focus of this work was to prevent further westward migration of the river and to protect key infrastructure and developments. This phase involved constructing 285 km of bank protection work and 40 km of groynes. The total investment of the project USD 5.59 billion (BDT 475 billion). It was indicated that the work could be completed by 2035, which would require extremely rapid implementation. Some elements of the plan are similar to FRERMIP, particularly the use of bend control to stabilize the planform. One difference is that the embankments appear to be set back substantially from the channel in the Yellow River study. Consequently, although the width of alluvial corridor is similar, the width of the flood corridor is much larger.

18.4 Capital Dredging Project

In 2011 BWDB initiated the *Capital Dredging and Sustainable River Management Project* following the directives of the Government of Bangladesh under a program for dredging of all the major rivers and land reclamation. The plan involves transforming the unstable Jamuna River into a narrower, meandering channel by dredging, accompanied by river training and flood embankment construction to confine the channel. Approximately 1.2 billion cubic meters of dredging would be required for constructing the river training measures alone. The total excavation volume (including channel deepening) is expected to be up to 36 billion cubic meters.

The capital dredging plan envisaged an annual investment of approximately BDT 640 billion (USD 7.7 billion) over a 15 year period to construct the stabilized channel. The capital cost over the 15 year construction period would exceed USD 110 billion. Approximately 94% of the project's capital cost is for dredging. Large-scale, perpetual maintenance dredging would be required in addition to these initial costs. International experience has shown that dredging as a river training method has only been successful on rivers with low sediment loads of coarse bed material. This is not the situation on the Jamuna or the Padma River.

18.5 Comparison of Plans

The four alternate river stabilization plans vary considerably in terms of their spatial extent, objectives, strategies and technical approaches. The BUET-BWDB and IWM studies are focused only on the Jamuna River, while the others include both the Jamuna and Padma Rivers. The differences in strategies and technical approaches to river stabilization illustrates the uncertainties and complexities in attempting to stabilize such a large, highly dynamic river system. Part of the difficulty lies in the limited understanding on how the different river reaches will respond to large-scale river training or dredging and the long-term response to attempts to narrow the river. The uncertainty in being able to forecast future trends in the river's behavior, in terms of its future channel instability and channel pattern changes also makes it difficult to prescribe comprehensive long-term river control programs. For these reasons, the IWM and BUET plans stress the need for adaptive planning and pilot project testing/verification of concepts as a key part of implementation. This adaptive approach is consistent with the FRERMIP RSP and with other international experience (Section 11).

The IWM and Yellow River Engineering Consulting Company (YRECC) plans focus primarily on river training measures to stabilize the river system. The YRECC plan uses a combination of bend control and node control with revetments and groynes, whereas the IWM plan proposes mainly permeable spurs. Although there are differences in the specific types of measures being proposed, the general concepts of the plans fall within the development pathways that have been identified in this plan (Section 14). The FRERMIP and YRECC plans share many similarities in terms of river training approach, channel alignment, and stable channel dimensions. The YRECC and IWM plans do not involve channelizing the braided section of the Jamuna River into a single meandering channel. The FRERMIP plan identifies three options in Reach 1 and Reach 2 of the Jamuna River. Under the present hydro-morphological regime, it is proposed to defer channel narrowing to a later date, until conditions are more appropriate and after additional investigations and pilot testing confirms that impacts can be properly managed. The BUET plan goes further and proposes to maintain the existing braided channel pattern by protecting the outer bank lines of the active channel.

Both the BUET plan and the Capital Dredging Project utilize large-scale, long term dredging programs to stabilize the rivers. The capital and maintenance costs of these dredging-based plans are much higher than for the plans that use primarily river training methods (FRERMIP, YRECC and IWM). The technical, environmental and economic feasibility of the dredging approach still needs to be confirmed.

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