

Jamuna–Brahmaputra River Natural Channel Design for Flood Control, Bank Erosion Protection, Navigation Improvement, and Land Reclamation



S. M. Bahar, K. W. Shushmi, M. A. Rafy, and Q. A. Mowla

1 Introduction

The Brahmaputra–Jamuna River system is one of the world’s largest, highly dynamic, sophisticated, and unpredictable braided rivers. The river is braided with metastable islands and nodal reaches, mobile sandbars, shifting anabranches, and severe bank erosion [1]. Systematic analysis of time series of dry season satellite images and with the supplement of available historical maps and aerial photographs, Center for Environmental and Geographic Information Services (CEGIS) reported that the Jamuna River shows a persistent trend of westward migration [2–5]. Analysis indicates that the centerline of the river has moved an average of 4.3 km toward west since 1830 with a maximum westward movement of 13 km at its northern end. In recent years, the Jamuna River is migrating westward at an average of 75 m per year [6]. Sarker and Thorne [7] proposed a hypothesis in their study that morphological changes in the Jamuna–Padma–Lower Meghna system have occurred in response to the sediment wave triggered by the Assam earthquake of 1950. Jamuna transformed into a multibraided channel from a less braided index channel by several bifurcation and minor channel development. Since the early 1970s, the Jamuna River has widened from 8.3 to 11.8 km in the mid-1990s. The Lower Jamuna River has undergone a similar transformation process, from reach-averaged width of 6 km in the 1970s to the increase to 10 km in the early 1990s [8]. Also, during the major flood of 1988, a

S. M. Bahar (✉) · K. W. Shushmi · M. A. Rafy · Q. A. Mowla
Ahydtech Water Resources (BD) Ltd, Dhaka, Bangladesh
e-mail: bahar@ahydtech.ca

K. W. Shushmi
e-mail: shushmi@ahydtech.com

M. A. Rafy
e-mail: rafy@ahydtech.com

Q. A. Mowla
e-mail: ashique@ahydtech.com

huge amount of sedimentation took place in the floodplain of Jamuna River which caused the development of two major channels in the lower reach of the river. These two channels are the main reason behind this unusual widening of the river along with insufficient sediment management. Due to this Great Assam Earthquake, sedimentation rate has increased in the Jamuna River. As a result, big islands like Char Alexander, Char Jobbar, etc., have been created. But recently the sediment wave has reached the Lower Meghna and its effect is diminishing [7]. This means that the channel patterns of the Jamuna tend to be more pronounced with fewer, deeper, and stable channels. As the widening phenomenon of Jamuna is decreasing, the Government of Bangladesh (GoB) is planning to reclaim thousands of acres of land lost into the riverbed. GoB has implemented some riverbank protection and flood control projects in Jamuna River funded by Asian Development Bank (ADB), World Bank, and other donor agencies for managing this heavily unpredictable and complex river system. Recently adapted “Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) Project-1” is a short-term ongoing riverbank protection and flood control project. Institute of Water Modeling (IWM) has conducted a study named “Jamuna River Economic Corridor Development Program” funded by the World Bank, that shows how land reclamation in Jamuna River can be done to transform the reclaimed area into an economic hub. Recently, IWFM and Bangladesh Water Development Board (BWDB) has developed a concept paper that proposes building a braided corridor to allow Jamuna River to move according to its own morphology. But all these studies focus on short-term solutions to the management of this complex river system including temporary river protection structure and dredging, which is not sustainable in the long run. In the year 2015, World Bank, under the River Management Improvement Program (RMIP), developed a long-term plan to narrow down Jamuna River to align it along a single corridor. Focusing on the flood remediation, river training, natural stabilizing, land reclamation, and sediment control of the Jamuna River, this study proposes a design of creating a 264 km long Natural Channel Design (NCD) of Jamuna River from Kurigram to Padma.

1.1 Objective of This Study

The main objective of this study is to-

1. Investigate the effect of narrowing down Jamuna River to develop a green, deeper corridor where the river will flow through different major and minor channels.
2. Develop an efficient sediment management program to eradicate navigation and flooding issues.

2 Methodology

As a part of the Jamuna River natural channel design, this study has reviewed available previous reports and studies on the Jamuna–Brahmaputra River. This study has collected secondary topography, bathymetry, flow, and water level data including aerial photograph from various sources. Digital elevation model (DEM) was created from aerial photographs. Using these data and information from the previous reports/studies, two 2D hydraulic models and a 2D sediment transport model have been developed with completed meander belt analysis and conceptual natural channel design of the Jamuna River.

2.1 2D Hydraulic Model

The Jamuna River in the study area causes severe flooding and erosion every year. To understand the existing Jamuna River flow conditions and to develop a conceptual natural channel design, two different 2D hydraulic models are developed using SMS SRH-2D software. One of the 2D hydraulic models uses 2011 bathymetry data to estimate the existing water level and flooding in the Jamuna River for low, bankfull, annual maximum and 100 year flow conditions. This model domain ranges from the Bangladesh–India border to the Padma River confluence. The model uses implicit finite difference methods with grid size varying from 220 to 450 m. At the upstream boundary of the model, flows from Bahadurabad gauge station (BWDB) are applied as inflow. A discharge vs water surface elevation rating curve is created and used at the downstream boundary. The model simulated results are analyzed to understand the existing flooding and flow conditions of the Jamuna River. A second 2D hydraulic model is developed from Gaibandha to the Ganges confluence for the analysis of an Initial Natural Channel Design (INCD). This INCD has a 2 km wide main river and 1.5 km wide floodplains on both sides of the main river. Topography and bathymetry of the INCD were created by a Geomorphic Innovative Technique (GeoITECH) software. GeoITECH used the existing Jamuna River upstream and downstream river invert elevations, and slope (0.0001). The main river of the INCD has meandering longitudinal profile with 1:3 bank slope and 12.0 m of depth. There are high embankments at the end of 1.5 km wide floodplains to contain the 100 year flood flow. Both left and right floodplains have a 0.2% ground slope from the embankment to the main river. It is assumed that the floodplains will be covered by vegetation, grass and plants, and the riverbanks with river protection measures to provide non-erodible surface in the model. This study has analyzed cross section, slope, and longitudinal profile to determine the main river bankfull cross section and combined cross-sectional area of the main river and floodplains. The model has applied low, bankfull, annual maximum and 100 year flows to perform hydraulic assessment of the INCD and to determine the main river and floodplain cross section.

2.2 2D Sediment Transport Model

The Jamuna–Brahmaputra River is one of the biggest braided rivers in the world, which has many bifurcations, islands, Chars, and settlements in Bangladesh. Based on available estimates, the river carries 260–720 Mt/year sediment load at its Bahadurabad gauge station. This high sediment load with a very mild river slope made it a highly dynamic braided river with significant sediment erosion and deposition. This study has developed a 2D sediment transport model using SMS and SRH-2D software. The model is about 46 km long from Gaibandha Sadar to Sariakandi. First 10.0 km of the model upstream has the existing Jamuna River shape and bathymetry of 2011. The remaining 36.0 km of the model has the INCD with main river and floodplains design. There is a transition reach of 3.0 km length from the existing Jamuna River to the INCD. GeoITeCH software was used to create topography and bathymetry of the INCD reach. The main river and floodplain slopes and cross sections were similar to the second 2D hydraulic model except for the 3.0 km transition reach. In the INCD reach, the floodplains are covered by vegetation and grass, and the riverbanks have protection measures. It is assumed that the floodplains, river banks, and embankments have non-erodible surfaces in the sediment transport model. The 2.0 km wide main river of the 36 km INCD reach and the 10.0 km long existing Jamuna River have erodible river bed. The model's governing equations are discretized using the finite-volume method. Its mesh containing both structured and unstructured elements is created using SMS Map Module. Element size is about 18 m in the banks and 45–50 m in the main river. In the floodplains, element size varies from 45 to 195 m. The model sediment transport parameters include sediment specific gravity, particle diameter, transport equation coefficient for suspended load (deposition and erosion), adaptation length for bedload transport (Philips-Sutherland Saltation length formula), and active layer thickness specification. It uses a total of eight sediment size bins with D_{50} of 0.26 mm to define sediment particle size distribution. This study used the Engelund–Hansen (1972) sediment transport equation for the mobile bed simulation. The river bed material was assigned through sediment material coverage. The model has two sediment materials: river and non-erodible. The river sediment material has two layers of sediment. Top layer is 0.5 m thick, and the second layer is 15 m. The top layer acts as an active layer for sediment that interacts in the water column. Both the layers need sediment particle size distribution through a gradation curve and sediment density (kg/m^3). At the downstream boundary, a flow vs water surface elevation rating curve was applied, and a steady-state flow was used at the upstream boundary. Similar to the 2D hydraulic model, the sediment transport model has also analyzed low, bankfull, annual maximum, and 100-year flows for sediment movement in the Jamuna River and in the INCD reach.

2.3 Meander Belt Analysis

Meander belt delineation is a tool for assigning a corridor in which meander migration may occur, with the ultimate goal of restraining development encroachment, minimizing the loss or damage of property, and protecting natural areas or sensitive habitats along river systems [9, 10]. Following this theory, this study has performed meander belt delineation of the 264 km long Jamuna River from the Bangladesh–India border to the Padma River confluence in order to determine the alignment of the natural channel. Initially, bathymetry data of 2008, 2011, 2017, and 2018 have been analyzed, and the meandering channel as well as the thalweg for each year was determined from the four years bathymetry data. Thalweg is defined as the line following the lowest elevation point along the riverbed. From the thalweg analysis, it was observed that, about 45 km upstream of the Padma–Jamuna confluence, the active channel of Jamuna River follows two major paths.

This study has defined and divided the Jamuna River into several reaches considering regional variation and sinuosity of the river. For each of the reaches, limits of the meander belt are defined by drawing parallel lines tangential to outside meanders of the reach. Meander axis is defined by determining the centerline of the meander belt. Meander amplitude and belt width determine the lateral extent of a river's occupation in the floodplain. Leopold [11] has defined meander amplitude as the lateral distance between tangential lines drawn to the center channel or meandering axis of two successive meander bends. On the other hand, meander wavelength is defined as the distance between two successive meander crest/trough.

Table 1 shows estimated values of meander wavelength and amplitude of each of the reaches. It is observed that maximum wavelength and amplitude of the Jamuna meandering channel have been found to be 32 km and 3.1 km, respectively, whereas minimum wavelength is 7.6 km and minimum amplitude is 0.35 km, approximately. The average wavelength and amplitude of the meandering channel are 15.6 km and 1.7 km, respectively.

Although the meandering channel represents the most active path of the river flow, alignment for the proposed natural channel had to be adjusted considering several indispensable factors which include: settlement near the river banks and existing chars, existing bank protection structures and other infrastructures, probable increase of flow velocity inside extreme bends, etc. These adjustments have been made by maintaining the maximum, minimum, and average limits of the wavelength and amplitude of the meandering channel as analyzed in Table 1. After adjusting the full meandering line, 2 km channel width has been provided along with 1.5 km flood plain on each side as shown in Fig. 1.

Table 1 Meander wavelength and amplitude analysis

Reach no.	Crest/trough	Meander amplitude(m)	Max meander amplitude (m)	Min meander amplitude (m)	Avg. meander amplitude (m)	Meander length (m)	Max meander length (m)	Min meander length (m)	Avg. meander length (m)
A	1	2945.51	2945.51	1366.24	2155.88	20,519.3	20,519.3	20,519.3	20,519.3
	2	1366.24							
B	1	1912.68	1912.68	899.63	1196.10	9324.38	9324.38	9010.27	9167.33
	2	899.63				9010.27			
	3	944.20							
	4	1027.9							
C	1	2326.22	2326.22	1536.87	1967.77	14,692	18,705.78	14,692	16,698.89
	2	1536.87				18,705.78			
	3	2040.22							
D	1	2922.92	3015.23	2922.92	2969.075	13,379.3	13,379.3	13,379.3	13,379.3
	2	3015.23							
E	1	1685.54	1906.74	354.90	1386.63	18,083.2	24,254.1	18,083.2	21,168.65
	2	354.90				24,254.1			
	3	1906.74							
	4	1599.33							
F	1	1891.68	2284.8	1340.88	1839.12	14,265.8	16,605.08	14,265.8	15,435.44
	2	2284.8				16,605.08			
	3	1340.88							
G(i)	1	3101	3101	2310	2705.5	31,702.1	31,702.1	31,702.1	31,702.1
	2	2310							
G(ii)	1	1062.54	1086	1062.54	1074.27	11,249.8	11,249.8	11,249.8	11,249.8

(continued)

Table 1 (continued)

Reach no.	Crest/trough	Meander amplitude(m)	Max meander amplitude (m)	Min meander amplitude (m)	Avg. meander amplitude (m)	Meander length (m)	Max meander length (m)	Min meander length (m)	Avg. meander length (m)
	2	1086							
H	1	1322	1322	1322	–	16,829.66	16,829.66	16,829.66	16,829.66
	1	1436.8	1520	1067.94	1286.19	10,326.2	12,214.1	10,326.2	11,384.71
I	2	1067.94							
	3	1120				12,214.1			
	4	1520							
	5	520	520	520	–	11,613.82			
	1	1427	2915	1427	2171	20,516.5	20,516.5	20,516.5	20,516.5
J	2	2915							
	1	381.18	2138.83	381.18	1260.01	7638.45	7638.45	7638.45	7638.45
K	2	2138.83							

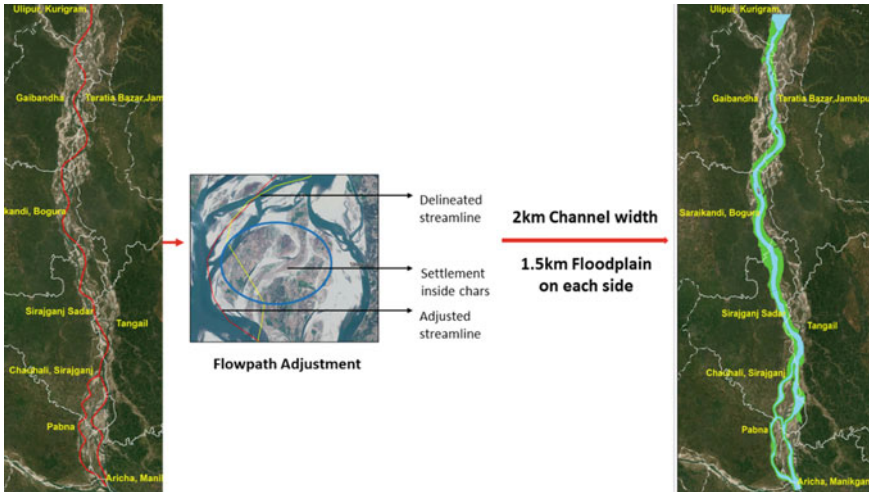


Fig. 1 Finalizing the alignment of the natural channel

2.4 Jamuna Natural Channel Design

This study attempts to propose a conceptual plan for flood protection, bank erosion control, navigation improvement, intake/offtake management, irrigation water supply, and land reclamation after incorporating results from the 2D hydraulic model, 2D sediment transport model, and meander belt analysis. The plan comprises four zones within the Jamuna River with different design criteria including sediment management, soft natural channel design, and comprehensive natural channel design using building with nature river training works.

Figure 2 below illustrates the conceptual plan and extents of the proposed four zones:

Detail components of the conceptual plan within the four zones are briefly described below:

Zone 1

“Do nothing” is proposed for the first 20 km reach of Jamuna River from the Bangladesh border. The plan proposes no intervention and channelization for this reach. Within this zone, Jamuna River will be untouched and kept as braided as it is.

Zone 2

This zone is about 45-50 km long from Kurigram to Gaibandha, which will gradually transit from the existing Jamuna River to the proposed natural channel design section of the conceptual plan. About 2.0 km wide main river and floodplain of 1.5 km on each side of the main river will be created with few minor channels through comprehensive

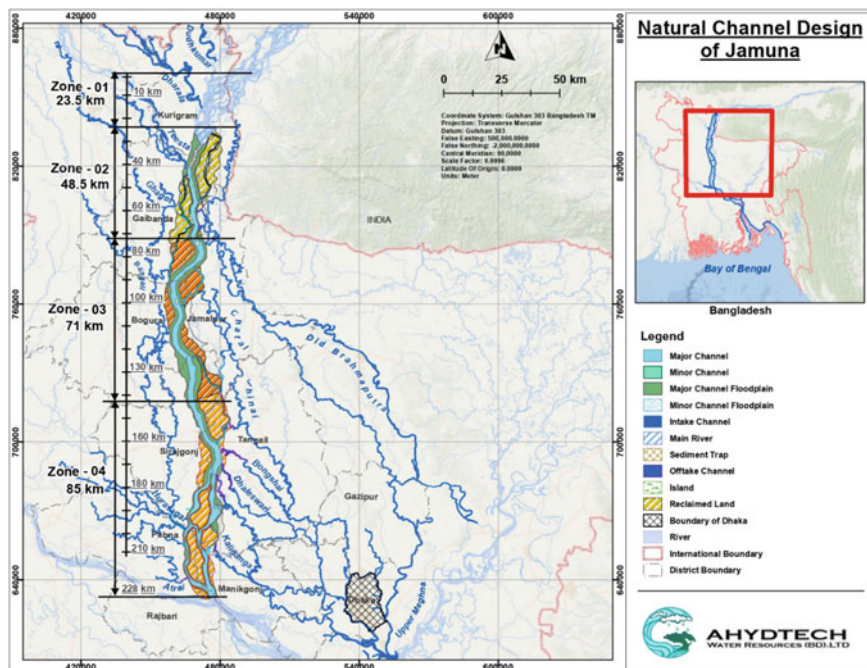


Fig. 2 Proposed four zones in Jamuna River

intervention and river training measures. A sediment trap will be constructed along the first 10–15 km of this zone for efficient sediment management.

Zone 3

In Zone 3, this study proposes a soft natural channel design along the 70 km stretch of Jamuna River starting from Sariakandi, Bagura to Sirajganj Sadar. The main river will be wide and deep enough to contain the bankfull flow. The main river will follow the existing Jamuna River thalweg and meandering, and the existing other bifurcation channels will be closed through connecting islands and chars except a few minor channels. This design will include soft natural channel design criteria, which will allow the river to move through erosion and deposition of sediment without creating bifurcations and braided channels.

Zone 4

In Zone 4, the conceptual plan has comprehensive natural channel design with main river, floodplains, embankment, and land reclamation. The conceptual plan in Zone 4 has two phases. These two phases are explained below:

Phase I: The Phase 1 of Zone 4 is about 34 km long, which starts from Sirajganj Sadar to 12 km downstream of Bangabandhu Bridge. Similar to the design of Zone 2, this phase of Zone 4 will have comprehensive sediment management and natural

channel design with compound channel cross section including the main river and floodplains.

Phase 2: The conceptual plan of Phase 2 starts from Chauhali, Sirajganj to Padma Confluence at Aricha, Manikganj. As shown in Fig. 2, there will be a large area of land reclaimed on both sides of this 5 km Jamuna River. The reclaimed land will be used for multimodal development purposes.

3 Results and Discussions

The Jamuna–Brahmaputra River in Bangladesh is one of the largest braided and dynamic rivers in the world, which carries a huge amount of sediment load every year causing erosion and deposition. The hydraulic analysis of the Jamuna River using 2011 bathymetry data and wide range of discharge indicates lateral extent of the river for different flow conditions. During the low flow, the river shows braided multiple channels, diversions, and bifurcations. These flow multiple channels and diversions have made the main channel inaccessible and unnavigable during dry periods due to sedimentation and lower flow. The river becomes 8–14 km wide during a bankfull flow of 48,000 m³/s and causes flooding and bank erosion every year. The hydraulic modeling of the 100-year flow shows further devastating flooding, which extends to over 55 km width of flooding.

The INCD and its hydraulic analysis indicate that it is possible to reduce the width of the Jamuna River to contain the flooding within the 5 km wide river with the 2 km of main channel and 1.5 km of floodplain on both sides of the main river. This INCD closes the minor channels, and then divert these to the main channel, which will make the main channel deeper with higher flow. This will eventually provide enough navigability even during low flow. The hydraulic model shows with low flow of 3000 cms, and the main channel provides a water depth of 2.2 m. The minor channels will be filled up naturally with sedimentation after 2–3 flood seasons. The floodplain will be designed to contain flood water during an extreme event. Results from the hydraulic modeling show that bankfull flow of 48,000 m³/s will be entirely contained within the main river, and flow as high as 100-year flow (123,000 m³/s) will be contained within the INCD, and thus prevent large areas from flooding.

The 2D sediment transport model was run for 10 days for a wide range of flows. Objectives of the model are to understand sediment transport rate and load in the existing Jamuna River and to manage sediment in the INCD. As excessive sediment load in the river is causing instability, dynamic and braided nature of the river, sediment management, and reduction of the sediment load are important components for successful implementation of the Jamuna natural channel design. The 46 km long model simulates sediment concentration, transport rate, and sediment load in the Jamuna River and INCD. This study analyzes the model simulated results at different cross sections of the model to compare sediment transport rate and load in the Jamuna River and INCD.

A total of nine cross sections (LN-1 to LN-9) was installed in the model to monitor/observe sediment erosion and deposition phenomenon. LN-1 and LN-2 are situated in the existing Jamuna River, whereas, from LN-3 to Line9 were in the INCD reach. Figure 3 represents the comparison of maximum sediment load that is observed in different locations of the channel for various flow conditions. This figure shows maximum sediment load (kg/m/s) vs discharge (m³/s) of five cross sections in the model of which LN-1 is located in the existing Jamuna River, and LN-6, LN-7, and LN-8 cross sections are in the INCD reach. The model simulated sediment load is highest in each cross section for bankfull flow (48000cms). Moreover, sediment load is extremely high in the existing Jamuna (LN-1). The sediment flow decreases when it enters in the INCD and subsequently reduces up to 50% in the downstream (Fig. 3). For 15,000 cms flow, sediment deposition occurs in the first 4–5 km of the INCD. The INCD bed’s disturbance, erosion, and deposition are very less in the downstream cross sections (LN-7 & LN-8). The sediment model for the bankfull flow (48,000cms) indicates sediment deposition is in the first 7–8 km of the INCD reach. Similarly, for this case, the INCD bed’s disturbance, erosion, and deposition are very less in the downstream cross sections (LN-7 & LN-8).

For the 65,000 cms overbank flow case, a significant portion of the flow is transferred through floodplain, and the bed disturbance is less compared to that of the bankfull case. The bed disturbance of the overbank flow propagates up to 5–6 km of the INCD reach. The INCD shows erosion instead of deposition in the first 7 km of the reach for the 100-year flow (103,000 cms) case.

The sediment model has run two simulations of flow (44,000cms), which is less than the bankfull flow. First simulation runs for 10 days, and second one for 20 days simulation. Results of the two simulations show that sediment deposition in the INCD further increases and propagates in the downstream if the simulation continues from

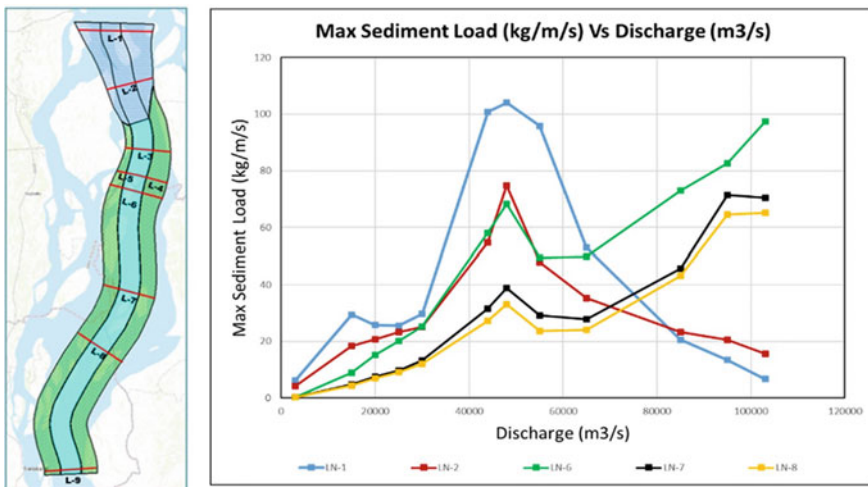


Fig. 3 Maximum sediment load (kg/m/s) vs discharge (m³/s)

10 to 20 days. After the 10 days simulation, sediment deposition occurred in the first 7 km of the reach. The sediment deposition length increased to 12–14 km after the 20 days simulation. Even after the 20 days simulation, the downstream cross sections still have very less bed disturbance. This analysis and result indicate that if the upstream section of INCD (about 7–10 km) is dredged every year, then the downstream INCD section will remain more stable river without exhibiting any significant erosion and deposition. The annual dredging of the upstream INCD will be helpful for proper sediment management in the Jamuna NCD.

It is evident that sediment load is the highest for bankfull flow (48000cms) at each of the cross sections. Moreover, sediment load is extremely high in the existing Jamuna. The sediment flow decreases when it enters the INCD and subsequently reduces up to 50% in the downstream (Fig. 3).

Figure 4 represents the cross-sectional bed elevation in the monitoring cross sections. The cross-sectional LN-1 shows river instabilities and bed elevation changes in the existing Jamuna River for different flow conditions. In the INCD, instabilities and bed elevation changes are limited in the main river. Cross-sectional LN-3 is in the upstream section of the INCD reach. This cross section shows deposition for flows at or below bankfull. For the overbank flows, especially during the 100-year flow, this section shows significant erosion. Further downstream, the natural channel bed remains almost undisturbed. For instance, in LN-3, the amount of deposition is significant. This deposited material must be dredged every year, and the natural channel has to be brought back to its original design condition for sediment management in the river. This will reduce the sediment disturbance downstream. In LN-7

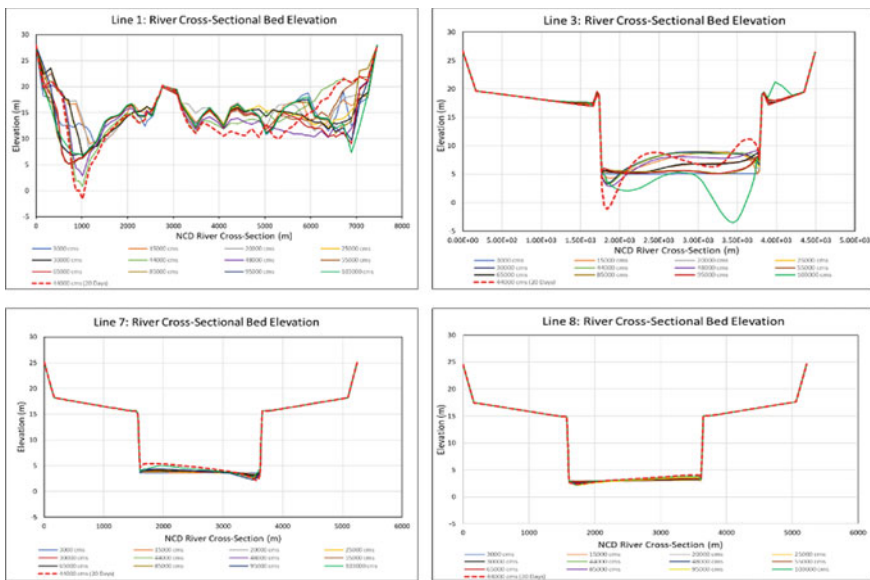


Fig. 4 Cross-sectional bed elevation of line 1, 3, 7, and 8

and LN-8, the INCD remains more stable than that of LN-3. It is evident that the rate of erosion and deposition is comparatively less in the INCD.

Analysis of sediment transport rate and load in Zone 1 will help to understand how the downstream river system can be managed including the proposed natural channel design, river morphology, sediment transport, bank erosion, and flooding. The results from 2D sediment transport modeling show that a large amount of sediment deposits in the upstream section (within the first 10–15 km) of the NCD of Zone 2. It is possible to create a sediment control basin within the section for sediment harvesting and dredging and eventually be controlled within this zone. Every year, deposited sediment will be harvested through dredging up to the level of original channel bed elevations created for the NCD and to maintain morphological balance. The dredged material can be used to fill and reclaim floodplain and construction of embankments. The present study indicates that if the upstream deposited sediment is dredged annually, the remaining section of the INCD will be almost stable and in equilibrium sediment transport conditions.

4 Conclusion

This study has collected and reviewed available reports, studies, and data on the Jamuna–Brahmaputra River. Based on the available information and data, and examples of NCD in the world, the study has prepared an INCD and conceptual plan for the Jamuna River Natural Channel Design. The plan and design consisting of four zones can provide multidimensional facilities such as land reclamation of 2018 sq. km which opens the door of immense possibilities like industrial zones, transportation, and newly developed cities. However, it needs further study and assessment on how much sediment load control is required for the sediment management in the Jamuna NCD. This INCD needs further study and analysis to improve the channel design and to accommodate and address environmental, ecological, social, and other issues and concerns. This study proposes different components and facilities within each zone to stabilize the course of Jamuna River for flood control and bank erosion protection. These components will collectively eliminate flooding, reduce lateral erosion, and stabilize the river by efficient natural channel design, river training, and sediment management. The conceptual plan will be confirmed by further hydraulic and sediment transport analysis to prepare the detailed design of the Jamuna Natural Channel. The analysis will provide information on what kind of measures will be required for the long-term stability of the proposed plan. The main river alignment will be derived from the meander belt analysis and the simulation results of the sediment transport model. From the simulation results, the study will observe how this natural channel will be moving within this zone. Though flow estimation from measured stages at Bahadurabad bears a lot of uncertainty, it will have influences on the result of the simulation. This is a limitation which requires further study and has a future study scope to simulate the natural channel movement more precisely.

References

1. Thorne CR, Russell APG, Alam MK (1993) Planform pattern and channel evolution of the Brahmaputra River, Bangladesh. *Geol Soc Spec Publ* 75:257–276. <https://doi.org/10.1144/GSL.SP.1993.075.01.16>
2. CEGIS (Center for Environmental and Geographic Information Services) (2004) Monitoring and prediction of Bank Erosion and Morphological Changes of the Jamuna and Padma Rivers Series
3. CEGIS (Center for Environmental and Geographic Information Services) (2005) Monitoring and prediction of Bank Erosion and Morphological Changes of the Jamuna and Padma Rivers Series
4. CEGIS (Center for Environmental and Geographic Information Services) (2006) Monitoring and prediction of Bank Erosion and Morphological Changes of the Jamuna and Padma Rivers Series
5. CEGIS (Center for Environmental and Geographic Information Services) (2007) Monitoring and prediction of Bank Erosion and Morphological Changes of the Jamuna and Padma Rivers Series
6. Nakagawa H, Zhang H, Baba Y, Kawaike K, Teraguchi H (2013) Hydraulic characteristics of typical bank-protection works along the Brahmaputra/Jamuna River, Bangladesh. *J Flood Risk Manag* 6:345–359. <https://doi.org/10.1111/jfr3.12021>
7. Sarker MH, Thorne CR (2009) Morphological response of the Brahmaputra–Padma–Lower Meghna River system to the Assam earthquake of 1950. *Braided Rivers* 289–310. <https://doi.org/10.1002/9781444304374.ch14>
8. ADB (2013) Main river flood and bank erosion risk management program final report, Annex E River and Charland Morphology and River Engineering. 292
9. Geomorph P (2004) Belt width delineation procedures. Submitted to the Toronto and Region Conservation Authority
10. Kline M, Cahoon B (2010) Protecting river corridors in Vermont. *J Am Water Resour Assoc* 46:227–236. <https://doi.org/10.1111/j.1752-1688.2010.00417.x>
11. Leopold LB, Wolman MG and JPM (1964) *Fluvial processes in geomorphology*. Dover Publications Inc., New York