Sustainable stabilisation of the Brahmaputra-Jamuna River in India and Bangladesh

Mosselman, Erik

DOI
10.1080/15715124.2025.2499872

Publication date
2025

Document Version
Final published version

Published in
International Journal of River Basin Management

International Journal of River Basin Management

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/trbm20

Sustainable Stabilisation of the Brahmaputra-Jamuna River in India and Bangladesh

Erik Mosselman

To cite this article: Erik Mosselman (06 May 2025): Sustainable stabilisation of the Brahmaputra-Jamuna River in India and Bangladesh, International Journal of River Basin Management, DOI: 10.1080/15715124.2025.2499872

To link to this article: https://doi.org/10.1080/15715124.2025.2499872

Published online: 06 May 2025.

INTERNATIONAL JOURNAL OF RIVER BASIN MANAGEMENT
https://doi.org/10.1080/15715124.2025.2499872

Sustainable stabilisation of the Brahmaputra-Jamuna River in India and Bangladesh

Erik Mosselman [a,b]

[a]Rivers department, Deltares, Delft, the Netherlands; [b]Department of Hydraulic Engineering, Delft University of Technology, Delft, the Netherlands

ABSTRACT
The Brahmaputra-Jamuna River in the plains of Assam (India) and Bangladesh is characterised by high bank erosion rates, cycles of widening and narrowing of its braid belt, unidirectional braid belt migration, and avulsions. The objective of this paper is to share insights in sustainable stabilisation of this river that have evolved in the past 30 years. Main benefits of stabilisation are the stopping of bank erosion outside its braid belt, avoidance of the breaching of embankments, provision of navigation channels to ports and ferry landings, and provision of stable distributary offtakes for freshwater supply. Often land reclamation by narrowing the river appears as an additional target. The paper argues that this has at least three adverse effects: (i) rise of flood water levels and decrease of hydraulic robustness; (ii) decrease of morphological robustness; (iii) potential tipping over of the fluvial system from a river responding horizontally to changes towards a river that incises its bed and responds vertically to changes. The paper discusses socio-economic implications and gives recommendations for sustainable stabilisation.

ARTICLE HISTORY
Received 11 November 2024
Accepted 26 April 2025

KEYWORDS
Brahmaputra; Jamuna; river training; bank erosion; river morphology

Introduction

Rivers worldwide have been profoundly modified by human interventions (Best 2019, Grill *et al.* 2019). Developed countries reaped benefits from extensive discharge regulation, river training and resource extraction in the 19th and twentieth century for safety against flooding, land reclamation, inland waterways, hydropower, freshwater supply and mining of construction aggregates. As time goes by, however, unintended side effects develop after decades or centuries, increasing maintenance costs, degrading the natural environment and leading to investments in mitigation infrastructure and ecological river restoration. Developing countries with less engineered rivers have an obvious desire and right to develop their rivers for obtaining similar benefits. The emerging understanding of potential long-term effects, however, calls for caution. The challenge is to develop sustainable river systems that provide benefits without causing regrets for future generations (Mosselman 2020). A complication is that developing countries sometimes resent this message of restraint if it comes from developed countries that did not exercise this caution themselves, or even represent former colonisers. Sharing the background of lessons learnt enables developing countries to evaluate the state of the art in knowledge and understanding of river behaviour themselves.

An example is the Brahmaputra-Jamuna River in India and Bangladesh. This roughly 10 km wide braided-anabranched sand-bed river is characterised by high bank erosion rates, cycles of widening and narrowing of its braid belt, unidirectional braid belt migration, and avulsions. It is being gradually stabilised to stop bank erosion outside its braid belt, to avoid the breaching of embankments, to provide navigation channels to ports and ferry landings, and to provide stable distributary offtakes for freshwater supply. In practice, narrowing the river to reclaim land often appears as an additional target. The corresponding environmental impact assessments of stabilisation works are usually limited to short-term local effects such as dredging plumes, noise of mechanical equipment, and the effect of tetrahedral porcupines on river dolphins. They seldom address large-scale long-term effects other than lip service to climate change. Meanwhile bold proposals to narrow the river linger on, often referring to a study by the Chinese-Bangladesh Joint Expert Team (CBJET 1991) to confine the Brahmaputra-Jamuna within an average width of 4.5 km. In China itself, however, based on thousands of years of experience with managing the Yellow River, Wang and Liu (2019) demonstrate that giving space to rivers is more sustainable in the long run than a strategy of narrowing the river with merely short-term benefits. Similar views constitute a growing consensus among experts in India and Bangladesh (e.g. Rahman *et al.* 2019), but the foundations of the views have not been presented systematically and are not broadly shared.

The objective of the present paper is to share insights in sustainable stabilisation of the Brahmaputra-Jamuna River that have evolved in the past 30 years. Parts of these insights have been published in scientific books and journals; parts only in less easily accessible project reports. The paper aims at informing decision makers, stakeholders, project advisors and scientists in India, Bangladesh and other

CONTACT Erik Mosselman erik.mosselman@deltares.nl Rivers department, Deltares, Boussinesqweg 1, Delft 2629 HV, the Netherlands; Department of Hydraulic Engineering, Delft University of Technology, Delft, the Netherlands
Associate Editor: Michael Nones

countries facing similar challenges of river engineering for sustainable economic development. This may form a common ground for discussion and empower stakeholders. Section 2 briefly introduces the river. Section 3 presents insights in the effects of narrowing, followed by a discussion of socio-economic aspects in Section 4. Section 5 closes the paper with conclusions and recommendations.

The Brahmaputra-Jamuna River

The about 2900 km long river has a catchment area of 560,000 km^2 (Figure 1). Its upstream part is the Yarlung Tsangpo in Tibet (China). After running east over more than 1100 km it enters the deep and steep Tsangpo Gorge between the mountain peaks Namche Barwa (7782 m) and Gyala Peri (7294 m). It passes the state of Arunachal Pradesh (India) through the Eastern Himalayas under the name Siang or Dihang and then flows west south west as Brahmaputra through the plains of Assam (India). At the Indo-Bangladesh border the river turns south and assumes the name Jamuna, valid strictly only downstream of the Old Brahmaputra offtake but in common usage already starting at the border. The name becomes Padma after its confluence with the Ganges at Aricha, and Lower Meghna after the confluence with the Upper Meghna at Chandpur, which debouches into the Bay of Bengal.

Coleman (1969), Goswami (1985), Thorne *et al.* (1993), Sarker *et al.* (2014), Best *et al.* (2022) and Rashid *et al.* (2024) present overviews of the river with special attention to its morphological dynamics. Pangare *et al.* (2021) add socio-economics, biodiversity, culture and governance. The Brahmaputra-Jamuna is the braided-anabranched sand-bed part of the river in the plains of Assam and Bangladesh. Its braid belt is about 10 km wide, with local widths up to 15 km. It has a marked monsoon hydrograph with an average discharge of 20,200 m^3/s, peak discharges up to around 100,000 m^3/s in July-September and minimum dry-season flows below 3000 m^3/s in January-March. In a distant past, glacial-lake outburst paleofloods reached values between 1 and 5 million m^3/s (Montgomery *et al.* 2004, Pickering *et al.* 2019). Bankfull discharge estimates range from 45,000–60,000 m^3/s (Thorne *et al.* 1993). Sediment load estimates range from 555 to 1157 Mt/year (Best *et al.* 2022), about one third of which is sand.

The river exhibits active planform changes by bank erosion and avulsion (Figure 2). Erosion can make the banks retreat by hundreds of metres in just a few months. The braid belt undergoes cycles of widening and narrowing, driven by hydroclimatic variations and variations in sediment supply from the catchment. The river avulsed roughly every 2000–3000 years between courses east and west of the uplifted Pleistocene Madhupur tract, up to 80 km apart (Goodbred and Kuhl 2000). The last avulsion from the eastern Old Brahmaputra to the western Jamuna developed between 1780 and 1880 (Bandyopadhyay *et al.* 2021, Islam *et al.* 2024). Part of the Brahmaputra avulsed 10 km southward around Dibru Saikhowa National Park in Upper Assam after 1992 (Kulnu *et al.* 2024). Bank erosion also drives unidirectional westward migration of the present braid belt at rates on the order of kilometres per century. Tectonics play a role (Fergusson 1863, Morgan and McIntire 1959, Mostafa *et al.* 2024) but are not the only mechanism (Sun *et al.* 2001). These planform changes pose huge challenges to the riparian countries. Bank erosion devours land, homesteads and infrastructure, including embankments built to protect wider areas against flooding. Siltation at the opposite side of migrating channels blocks navigation channels to ports and ferry landings, and closes the entrances to distributary rivers that are important for freshwater supply.

Stabilisation works have been carried out over the past 30 years to keep the braid belt at its place, to prevent the breaching of embankments, and to provide stable distributary offtakes for freshwater supply as well as access for navigation to ports and ferry landings. These works have boosted innovations in bank protection, river training and the monitoring and prediction of river planform changes. After having piloted different bank revetments, permeable groynes and temporary structures such as top-blocked spurs or high-water bandals in the 1990s (described by Mosselman 2006), an effective revetment technology emerged based on geobags (Oberhagemann *et al.* 2020). Satellite remote sensing has been used to analyse river planform changes (Bristow 1987, Klaassen and Masselink 1992) and to develop morphological prediction methods using explicit empirical rules (Klaassen *et al.* 1993, EGIS 2002), machine learning (Jagers 2001, Magherini 2024), and physics-based numerical modelling (Enggrob and Tjerry 1999, Giri *et al.* 2021).

Effects of river narrowing

Decrease of hydraulic robustness

Narrowing of the flood corridor between embankments will raise flood water levels and require higher embankments (Figure 3). The surrounding land then becomes more vulnerable to floods if an embankment is breached, rendering the river less robust from a flood risk management perspective. Klijn *et al.* (2019) also point at another decrease of hydraulic robustness. Narrowing will increase the differences between the water levels at different discharges. A slight increase in design discharge will then involve a larger rise of the design flood levels with more substantial demands of embankment reinforcements. This renders the flood defence system of the river less robust in view of future demands for safety against flooding.

How narrowing affects water levels can be calculated for steady uniform flow through an idealised rectangular river cross-section by combining the Chézy equation (Equation 1) with the definition of discharge (Equation 2):

$$u = C\sqrt{hi} \quad (1)$$

$$Q = Bhu \quad (2)$$

where u denotes depth-averaged flow velocity, C the Chézy coefficient for hydraulic roughness, h flow depth, i streamwise slope, Q discharge and B river width. The combination results in

$$Q = BCh^{3/2}i^{1/2} \quad (3)$$

Equation 3 shows that, for constant Q, C and i, a decrease in river width will increase flow depth and equally raise the water level if the bed level is still the same. The new water depth, h_1,

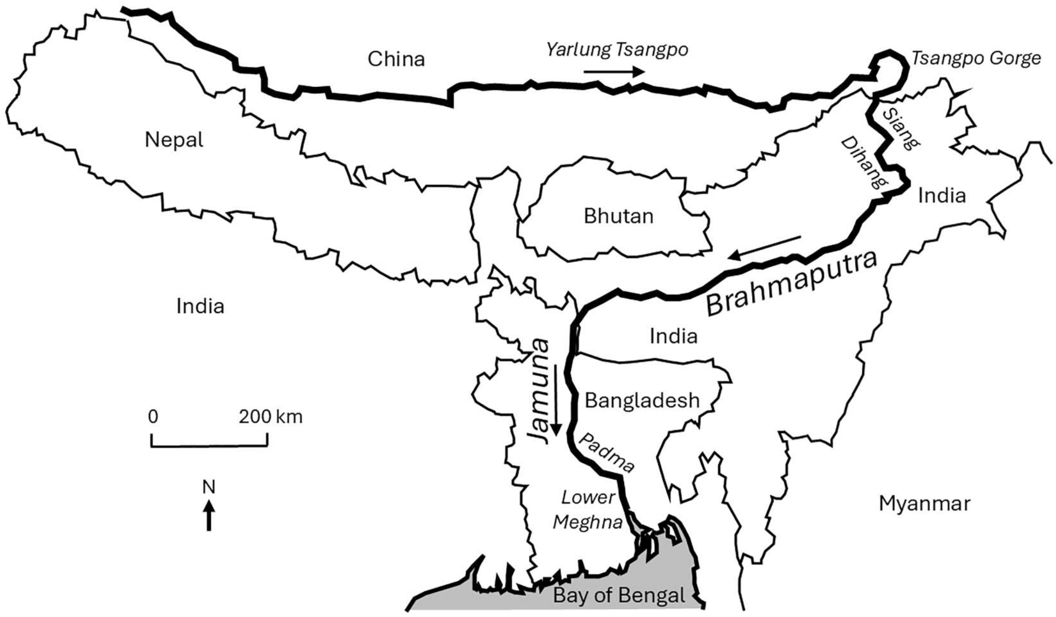

Figure 1. Geographical setting.

after narrowing from B_0 to B_1 can be calculated from

$$h_1 = \left(\frac{B_1}{B_0}\right)^{-2/3} h_0 \tag{4}$$

Decrease of morphological robustness

ISPCM (2019b) estimates the recurrence interval. Discharge and sediment supply of the Brahmaputra-Jamuna vary interannually, interdecadally and over longer time scales, in response to changes in precipitation, use of land and water, tributary avulsions, and earthquakes in the catchment. They are expected to continue doing so. Nelson *et al.* (2024) relate interdecadal width changes to hydroclimatic variations. Large morphological changes in Assam and in Bangladesh have been documented and ascribed to pulses of sediment load that were generated by the Shillong Earthquake in 1897 (Goswami and Das 2002) and the Great Assam Earthquake in 1950 (Sarker and Thorne 2006, Sarker *et al.* 2014). Major earthquakes are frequent in the catchment, as the region experienced 20 earthquakes of Richter magnitude >7 in the past century (Best *et al.* 2022). ISPCM (2019b) estimates the recurrence interval of upstream earthquakes to be 100 years for magnitude 7.6 and 450 years for the magnitude 8.6 of the 1950 Great Assam Earthquake. For the coming century (2025-2124) the probabilities of occurrence of at least one other such earthquake are hence $[1-(1-1/100)^{100}] \times 100\% = 63\%$ for magnitude 7.6 and higher, and $[1-(1-1/450)^{100}] \times 100\% = 20\%$ for magnitude 8.6 and higher. These probabilities cannot be ignored in long-term planning.

The morphological response to sediment overloading consists of vertical riverbed aggradation (Ribberink and Van der Sande 1985, Goswami and Das 2002), horizontal intensified braiding (Germanoski and Schumm 1993), and horizontal widening of the braid belt. Sarker and Thorne (2006) and Sarker *et al.* (2014) report that the river in Bangladesh has widened from 8.5 km in 1973–12.2 km in 2009 and ascribe this to increased sediment loads after the 1950 Great Assam Earthquake had triggered 45 cubic kilometres of landslides. The morphological response to the sediment pulse travels like a wave downstream. The physical mechanisms underlying the associated widening have been subject to debate. Thorne (1996) proposes that overbank flows driven by bed aggradation excise new channels in the floodplain. Another explanation for widening could be that higher flow velocities due to water level drawdown above the front of the bed aggradation wave erode the riverbanks (Figure 4).

The natural cycles of widening and narrowing on decadal and longer time scales imply that a sufficiently wide erodible corridor (Piégay *et al.* 2005) needs to be kept available to cope with future changes in upstream hydrology and sediment supply, avoiding lock-in situations that would cause regrets for future generations. Thorne (1993) already advocated this morphological robustness as a precautionary principle in a time when long-term planform variability was less well known and understood. The later insights reported in the present paper support his plea.

Passage of erosion tipping points

Starting from an untrained condition, the river responds to narrowing mainly horizontally by eroding islands and bars ('chars') without significantly affecting the morphology of the main channels. When narrowing proceeds, however, the predominant horizontal planform response turns into a predominant vertical riverbed elevation response. Although the transition is gradual, this change of response regime can be seen conceptually as the passage of a tipping point. Riverbed erosion causes lower water levels in the dry season which entail problems for irrigation and freshwater supply, and lead to drying of connected floodplains and wetlands. In particular, it would reduce the water flows to the Dhaka Metropolitan Area through the distributary rivers Old Brahmaputra and Dhaleswari. The bed erosion would also produce deeper scour at hydraulic structures.

The short-term riverbed elevation response to narrowing differs from the long-term response because initial

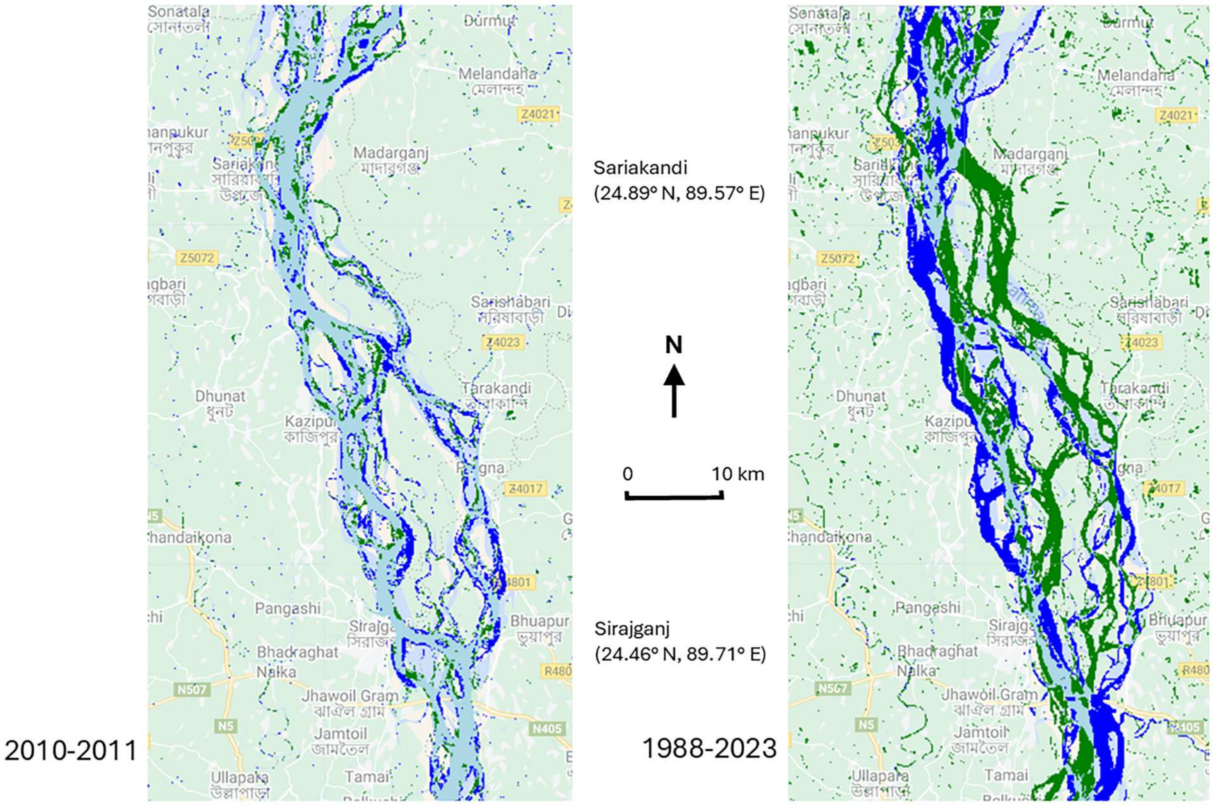

Figure 2. Morphological planform changes of the Jamuna River between Sariakandi and Sirajganj in 1 year (left) and 35 years (right). Blue indicates erosion, green accretion. The changes in 2010–2011 show growth of an eastern anabranch and clear examples of outer-bend erosion. The changes in 1988–2023 reveal the unidirectional trend of westward migration. Source: Bangladesh Erosion Monitor, based on Google Earth Engine and derived from Aqua Monitor (Donchyts *et al.* 2016).

sedimentation upstream and downstream of the narrowed reach disappears or even turns into erosion in the long run. Figure 5 shows a longitudinal profile of the short-term response, exaggerating vertical dimensions with respect to horizontal ones for clarity. The narrowing initially raises water levels according to equations for gradually-varied steady flow (backwater equations). The resulting spatial variations in flow depth produce spatial variations in flow velocity. The effect of these variations on the riverbed can be understood from the following simplified analysis for a river with idealised rectangular cross-sections. The volumetric mass balance for sediment can be written as.

$$\frac{\partial z_b}{\partial t} + \frac{\partial q_s}{\partial x} = 0 \tag{5}$$

where z_b denotes riverbed level, q_s sediment transport rate per unit width (including the pores of presence in the riverbed), t time and x streamwise coordinate along the river. Following Exner (1925), the sediment transport rate can be related to flow velocity. A suitable general relation for sand

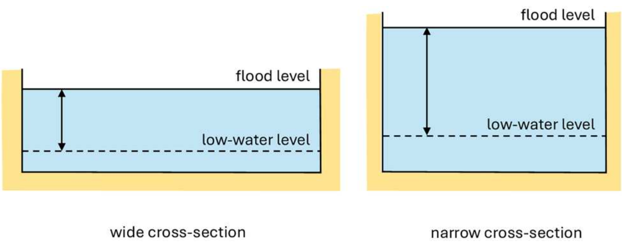

Figure 3. Schematic representation of the effects of narrowing between embankments on flood levels.

reads

$$q_s = mu^b \tag{6}$$

where m is a coefficient and exponent b represents the degree of nonlinearity of the relation between flow velocity and sediment transport. Physically realistic values require $b > 3$ (Mosselman 2005). For smaller sand-bed rivers and laboratory flumes $b = 5$ holds well, in accordance with the semi-empirical predictor of Engelund and Hansen (1967). For large sand-bed rivers, $b \approx 4$ (Molinas and Wu 2001). A measurement campaign of the River Survey Project in Bangladesh found $b = 3.66$ for the Brahmaputra-Jamuna (Delft Hydraulics and DHI 1996).

Substitution of Equation (6) into Equation (5) and application of the chain rule for differentiation gives the Exner equation

$$\frac{\partial z_b}{\partial t} + b\frac{q_s}{u}\frac{\partial u}{\partial x} = 0 \tag{7}$$

This explains the initial effect on the riverbed in Figure 5. Upstream backwater and associated flow deceleration ($\partial u/\partial x < 0$) lead to sedimentation ($\partial z_b/\partial t > 0$). The abrupt increase in flow velocity at the upstream end of the narrowed reach produces erosion that further advances as a rarefaction wave. The drawdown of the water level and associated flow acceleration towards the downstream end of the narrowed reach erode the riverbed too. The abrupt drop in flow discharge downstream generates sedimentation that further expands as a shock wave.

Figure 6 shows new equilibria that are eventually reached on a long term. Erosion leads to new longitudinal profiles

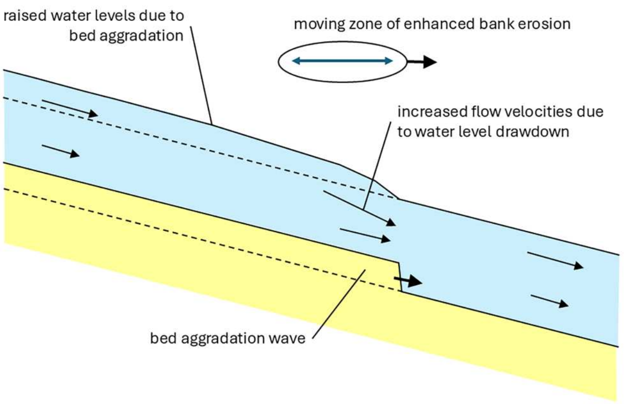

Figure 4. Proposed mechanism of enhanced bank erosion above front of bed aggradation wave. Flow velocities increase as the flow concentrates in a smaller water depth.

with piecewise uniform river reaches. The mass balance for sediment (Equation 5) then degenerates into the condition that each reach conveys the same total load of sediment and hence satisfies

$$Q_s = Bq_s \tag{8}$$

where Q_s denotes total sediment load. Substitution of Equation (6) and subsequent elimination of flow velocity through Equations (1) and (2) result in

$$Q_s = Bm(u^2u)^{b/3} = Bm\left(C^2hi\frac{Q}{Bh}\right)^{b/3} = B^{1-b/3}mC^{2b/3}Q^{b/3}i^{b/3} \tag{9}$$

$$Q_s = B^{1-b}mQ^bh^{-b} \tag{10}$$

Equation (9) shows that the new slope, i_1, in the reach narrowed from B_0 to B_1 can be calculated from

$$i_1 = \left(\frac{B_1}{B_0}\right)^{1-3/b} i_0 \tag{11}$$

which implies that smaller widths always lead to flatter slopes because $b > 3$. Equation (10) shows that the new water depth, h_1, after narrowing from B_0 to B_1 can be calculated from

$$h_1 = \left(\frac{B_1}{B_0}\right)^{1/b-1} h_0 \tag{12}$$

which implies that smaller widths always lead to larger depths.

Figure 6 shows that the river will erode its bed not only in the narrowed reach but also far upstream. The amount of erosion will be modest if only a short river reach is narrowed (Figure 6, right), but large if the narrowed reach is long (Figure 6, left). It is the cumulative length of narrowed reaches that determines the depth of bed erosion.

More sophisticated computations using physics-based 2D numerical models for river morphology give similar results. Simulations by IWM (2019) suggest that narrowing the river to widths between 5 and 8 km could erode the riverbed and lower the dry-season water levels by up to 5 m within 20 years. The computational grid was coarse and the model had not been calibrated or verified morphologically, but the rates of sediment transport complied with measurements. The results therefore do give an indication of the order of magnitude of possible effects.

An extension of Equations (1) to (12) to compound cross-sections of channels and bars with an empirical relation for planform response makes the predicted erosion less deep (ISPCM 2019a). Two other factors, however, suggest that the real erosion could be deeper than predicted by the analytical models and 2D numerical models. First, bank stabilisation will make bend scour deeper (Mosselman *et al.* 2000) and, in combination with narrowing, it will cause local scour to occupy and affect larger areas of the overall morphology (Mosselman and Sloff 2002). Second, the weak dependence of sediment transport on flow velocity expressed by $b = 3.66$ from the River Survey Project (Delft Hydraulics and DHI 1996) might reflect that part of the measured sediment stemmed from slowly settling plumes generated by rapid bank erosion upstream, to which Equation (6) does not apply. Bank stabilisation would eliminate these sediment plumes and thereby increase the value of b if Equation (6) would be calibrated on corresponding new data. This would enhance erosion in Equations (11) and (12).

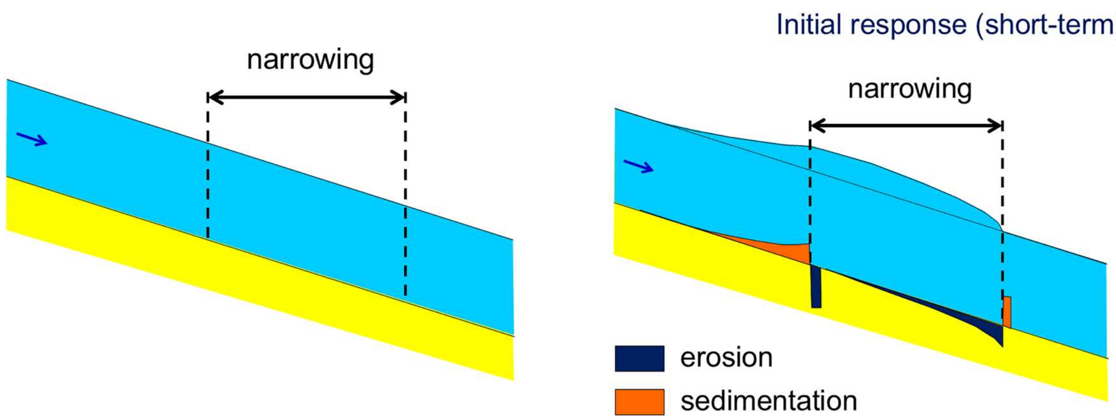

Figure 5. Schematic representation of short-term morphological effect of narrowing on longitudinal river profile. Left: before narrowing. Right: immediately after narrowing.

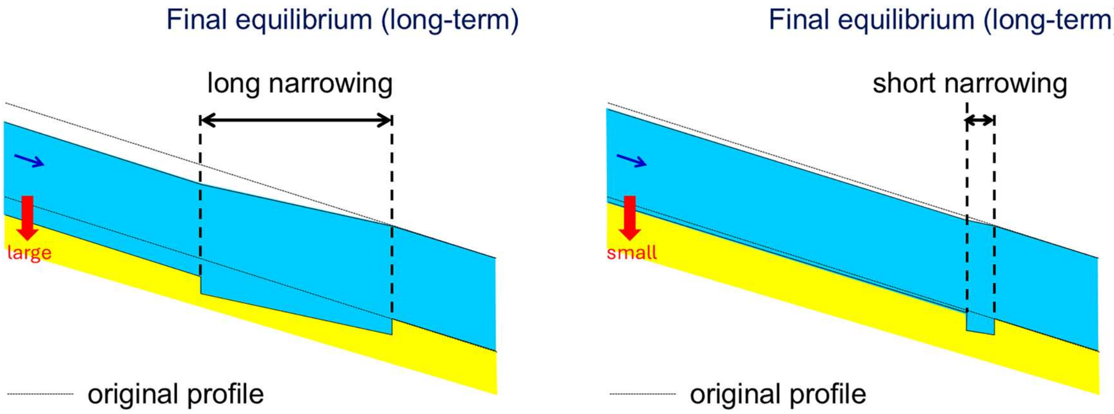

Figure 6. Schematic representation of long-term morphological effect of narrowing on longitudinal river profile. Left: narrowing of a long river reach. Right: narrowing of a short river reach.

Socio-economic implications

Land reclamation

Narrowing of the river to reclaim lost agricultural land often appears as an additional target of river stabilisation. As the value of agricultural land is low, local economic analyses often exaggerate the benefits, for instance by assuming that reclaiming a 200 km long and 4 km wide strip of land along the river would create 800 km^2 of economic zones, urban development, industries and ecotourism resorts. Moreover, cost–benefit analyses usually do not consider the costs of the adverse effects of narrowing. Additional issues are social problems around land grabbing and reduction of habitats for birds by the erosion of bars and islands.

Limited land reclamation might do little harm from a mere morphological viewpoint as long as it does not compromise hydraulic robustness, morphological robustness or passing the tipping point for widespread riverbed erosion. Little harm is plausible in particular when reclaiming abandoned channels that are relics from migration of the braid belt and give the river an overwide appearance. Care must then be taken of maintaining connectivity for the livelihood of local communities and ecosystem services. This involves maintaining unhindered flows and sediment transport from tributary rivers and drainage channels, as well as preserving wetlands and habitats.

Figure 7. Ship on the Jamuna River near Sirajganj in Bangladesh, not heavily loaded.

Navigation

India and Bangladesh signed a Protocol on Inland Water Transit and Trade (PIWTT or PIWT&T) to make mutually beneficial arrangements for the use of waterways for commerce between the two countries. The transboundary Brahmaputra-Jamuna River is a route under this protocol as part of Indian National Waterway 2. In its guidelines for sustainable management of the navigability of natural rivers, PIANC (2024) presents a vision on the development of an inland waterway between the Indo-Bangladesh border and Sirajganj in Bangladesh. This vision could be extended to the Brahmaputra in Assam.

Shoals prohibit that vessels are loaded to full capacity in the dry season (Figure 7), but the number of cargo vessels transiting over the Brahmaputra-Jamuna River is too small to justify immediate large investments for increasing the available depth. Moreover, moderate narrowing of the braid belt would not do much for navigability as it would mainly reduce the area of bars and islands. PIANC (2024) recommends focusing initially on increasing the reliability of the waterway to ensure safe and predictable passage. If demand increases, further investments can be made for subsequent phases of development. Structural interventions will then primarily regard the stabilisation of connections to ports, ghats, river junctions and other navigational facilities. River training for navigation is ideally based on low-crest structures that favour a single channel and increase the navigation depth at low flows, without affecting flood flows and overall river width. A future end point for a fully developed waterway could be based on a parallel canal with ship locks.

PIANC (2024) recommends starting with dynamic management of navigation channels that change position by morphological development. This management involves frequent bathymetric surveys, frequent hydrographic chart updates, local infrastructure, bottleneck dredging, and aids to navigation such as buoys that can be repositioned quickly, several times per season. Dynamic navigation management would be supported by on-board radar or VHF communications for night navigation, inland electronic navigation charts (IENC), Automatic Identification System (AIS) services, and notices to skippers with quasi-real-time information on the latest position of the channel. Existing water gauges could be supplemented by water level sensors and telemetry. No narrowing is recommended.

Sediment mining

Fluvial sands and gravels are of great value as construction aggregates, but worldwide awareness is growing that mining these sands from riverbeds has adverse effects (GEAS 2014). Mining lowers the river bed with similar adverse effects as narrowing of the river. Sand mining is therefore considered one of the greatest causes of environmental degradation in the rivers of South and South-East Asia. In South India water aquifers disappear as relatively thin layers of alluvial deposits are removed from river valleys above the hard crystalline rocks of the Deccan Plateau. That is why it is generally recommended to abstain from mining sands and gravels from main river channels and to dredge river channels for navigation with a closed balance, i.e. by depositing dredged material in deeper parts of the river or areas outside the navigation channel.

The situation in the Brahmaputra River, however, is different, because it experiences episodes of sediment overloading and riverbed aggradation due to mobilisation of sediments from the catchment by earthquakes. In principle therefore, sand can be mined from the Brahmaputra River. Care remains nonetheless necessary that sand is not mined indiscriminately but that this resource is managed properly. Permits for mining sand need to be based on thorough assessments of resource availability and impacts. Locations of mining need to be selected with care too. Borrow pits close to riverbanks attract flow in the monsoon and thereby enhance bank erosion or increase the loads on bank protection.

River management

The morphological processes in the river are so dynamic that changes occur faster than can be followed in ordinary modelling, design and implementation. Available data quickly become outdated. This calls for high flexibility in the planning, design, tendering and implementation of works. It also puts master plans for river development in another perspective. Commonly master plans present detailed maps of future shape and a timeline for implementation of programmed infrastructural works. Such a level of detail is not possible for the rapidly changing Brahmaputra-Jamuna River. Moreover, the very contact with revetments and groynes makes individual channels narrower and deeper, irrespective of the corridor width (Mosselman *et al.* 2000). This reduces the natural wavelength of meandering channels in the braid belt too. Nonetheless, drawings are needed for calculating costs, assessing environmental and social impacts, and comparing different options for a suitable course of action. These drawings constitute a reference programme which should not be mistaken as a definitive blueprint for future river works, with future alignments of riverbank protection and river training. The drawings could be updated every five years to account for changes in the river and to include lessons learnt. Rather than presenting a blueprint for the future river, the river stabilisation plan conveys a design philosophy that accounts for the uncertainties in river response and gradual implementation of works over decades. The philosophy would be based on flexibly adapting plans to morphological development, seizing opportunities offered by the river, continuous monitoring and predicting, learning by doing, and seeking sustainable interventions that do not cause regrets to future generations under a variety of scenarios. To the latter end, interventions should leave room for later adjustments, considering narrowing of the river only with great caution.

Stabilisation works are often planned, designed and implemented at the level of local districts, without strong oversight and guidance by a central organisation. Flowing through different countries complicates this even more. Different districts may compete for funding, sometimes driven by maximising financial resources or maximising land reclamation. Districts also commonly lack knowledge of the morphological functioning of the river and hold misconceptions such as the idea that widening of the braid belt after the Great Assam Earthquake in 1950 was a rare anomaly. As a traditional map-based masterplan of training works is not suitable for the Brahmaputra-Jamuna, ministries might consider central guidance and legislation by mapping zones in the braid belt where no river training encroachment is permitted. These zones would form an erodible corridor. Contrary to erodible corridors in the context of river restoration (Piégay *et al.* 2005), however, this delineation would not give more space to the river but rather constrain the possibilities of reducing space.

Institutional aspects

The Ministries of Water Resources, responsible for river stabilisation, have a predominantly civil engineering perspective. Affected local communities are informed and interviewed as part of projects, but at times, as I witnessed, by persons who do not know the objectives, the scope of work and the expected effects themselves. This hampers dialogue and inclusion of local knowledge. A representative of a fishermen community in the Sonitpur District of Assam, for instance, expressed an intelligent vision on stabilising the river while keeping sufficient space for hydraulic functioning and fisheries, but such visions are not easily mobilised in current decision making.

The necessity of timely reacting to rapid developments of the river forms another bottleneck. Technically, the lead time of data collection and modelling has decreased a lot (Giri *et al.* 2021) but administrative procedures remain long. Works are often carried out in discontinuous projects with limited duration, lacking continuity in river surveys and the management of databases. Some funds are released during emergencies only, when proper study, design and implementation is not possible.

Conclusions and recommendations

River engineering works have been stabilising the Brahmaputra-Jamuna River over the past decades and can be expected to be continued. The main objectives are to stop bank erosion outside its braid belt, to avoid the breaching of embankments, to provide navigation channels to ports and ferry landings, and to provide stable distributary offtakes for freshwater supply. In addition to these benefits, narrowing the river to reclaim land often appears as an additional target. However, this has at least three adverse effects. First, narrowing of the river between embankments will raise flood water levels and reduce hydraulic robustness from a flood risk management perspective. Second, taking away the space for coping with changes in hydroclimate and sediment yield of the catchment will reduce morphological robustness. Third, narrowing could make the fluvial system tip over from a river responding horizontally to changes towards a river that incises its bed and responds vertically to changes.

These effects have socio-economic implications. Land reclamation requires serious caution and often is not justified by cost–benefit analyses. Only reclamation of abandoned riverbeds as relics from braid belt migration might cause little harm. Mere narrowing of the braid belt is ineffective for improving navigability as it would mainly affect bars and islands rather than channels. It is recommended to improve navigability by dynamic navigation management based on frequent bathymetric surveys, frequent hydrographic chart updates, local infrastructure, bottleneck dredging, and aids to navigation. This would be supported by modern sensor, information and communication technologies. Experts generally advise against mining sand and gravel from main river channels, but episodes of sediment overloading and riverbed aggradation in the Brahmaputra do offer possibilities for mining, provided that this is managed properly.

The Brahmaputra-Jamuna requires flexible management that can adapt to fast morphological changes. Rather than preparing blueprints for layouts of future river works, central authorities could map zones where no river training encroachment is permitted. From an institutional point of view, it is recommended to involve stakeholders more thoroughly in decision making, and to move from discontinuous and emergency-based actions towards continuous work, supported by monitoring, modelling and scientific research.

Acknowledgements

The contents of this paper are based on experiences from the Jamuna Multipurpose Bridge Project, the components FAP21, FAP22 and FAP24 of the Flood Action Plan, the Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP), the Brahmaputra-Jamuna River Economic Corridor Development Program, all in Bangladesh, and the Climate Resilient Brahmaputra Integrated Flood and Riverbank Erosion Risk Management Project in Assam. The writing of this paper has been funded by the SITO-IS 2024 programme in Deltares.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

Erik Mosselman is a river scientist and hydraulic engineer with special expertise in fluvial morphodynamics, river training, ecological river restoration and flood risk management. He has been involved in projects on the Brahmaputra-Jamuna River since 1992.

ORCID

Erik Mosselman http://orcid.org/0000-0002-4335-5085

References

Bandyopadhyay, S., Das, S., and Kar, N.S., 2021. Avulsion of the Brahmaputra in Bangladesh during the 18th-19th century: A review based on cartographic and literary evidence. *Geomorphology*, 384, 107696. doi:10.1016/j.geomorph.2021.107696.

Best, J., 2019. Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, 12, 7–21. doi:10.1038/s41561-018-0262-x.

Best, J.L., *et al.*, 2022. The Jamuna–Brahmaputra River, Bangladesh. Chapter 20. In: A. Gupta, ed. *Large Rivers: Geomorphology and Management*, 2nd ed. Oxford, UK: Wiley-Blackwell, 579–640. ISBN: 978-1-119-41260-1

Bristow, C.S., 1987. Brahmaputra River: channel migration and deposition. In: F.G. Ethridge, R.M. Flores and M.D. Harvey, eds. *Recent developments in fluvial sedimentology*. Tulsa (OK), USA: Special publication No.39 of Society of Economic Palaeontologists and Mineralogists, 63–74.

CBJET, 1991. *Study report on flood control and river training project on the Brahmaputra River in Bangladesh*. China-Bangladesh Joint Expert Team: Dhaka, Bangladesh, March 1991.

Coleman, J.M., 1969. Brahmaputra River: channel processes and sedimentation. *Sedimentary Geology*, 3 (2-3), 129–239.

Delft Hydraulics and DHI, 1996. *River survey project; sediment transport predictors*. Special Report No.13, Water Resources Planning Organization, Government of Bangladesh: Dhaka, Bangladesh.

Donchyts, G., *et al.*, 2016. Earth's surface water change over the past 30 years. *Nature Climate Change*, 6, 810–813. doi:10.1038/nclimate3111.

EGIS, 2002. *Developing and updating the empirical methods for predicting the morphological changes in the Jamuna River*. Technical Note Series 29, Environmental and GIS Support Project for Water Sector Planning: Dhaka, Bangladesh.

Engelund, F., and Hansen, E., 1967. *A monograph on sediment transport in alluvial streams*. Copenhagen, Denmark: Teknisk Forlag.

Enggrob, H.G., and Tjerry, S., 1999. Simulation of morphological characteristics of a braided river. *In: Proceedings of the IAHR Symposium on River, Coastal and Estuarine Morphodynamics*: Genoa, Italy, 6–10 September 1999, I, 585–594.

Exner, F.M., 1925. Über die Wechselwirkung zwischen Wasser und Geschiebe in Flüssen. *Sitzungsberichte Akademie der Wissenschaften*: Vienna, Austria, pt.IIa, 134 (2) 165-203.

Fergusson, J., 1863. On recent changes in the delta of the Ganges. Proceedings of the Geological Society: London, UK, *Quaternary Journal*, 19 321-354.

GEAS, 2014. *Sand, rarer than one thinks*. UNEP Global Environmental Alert Service. https://na.unep.net/geas/archive/pdfs/GEAS_Mar2014_Sand_Mining.pdf [Accessed 11 November 2024].

Germanoski, G., and Schumm, S.A., 1993. Changes in braided river morphology resulting from aggradation and degradation. *Journal of Geology*, 101, 451–466.

Giri, S., *et al.*, 2021. Stabilization of the Lower Jamuna River in Bangladesh – Hydraulic and morphological assessment. *Geosciences*, 11, 389. doi:10.3390/geosciences11090389.

Goodbred Jr., S.L. and Kuehl, S.A., 2000. The significance of large sediment supply, active tectonism, and eustasy on sequence development: Late Quaternary stratigraphy and evolution of the Ganges–Brahmaputra delta. *Sedimentary Geology*, 133, 227–248.

Goswami, D.C., 1985. Brahmaputra River, Assam, India: physiography, basin denudation and channel aggradation. *Water Resources Research, AGU*, 21 (7), 959–978.

Goswami, D.C., and Das, P.J., 2002. Hydrological impact of earthquakes on the Brahmaputra river regime, Assam: A study in exploring some evidences. *My Green Earth*, 3 (2), 3–13.

Grill, G., *et al.*, 2019. Mapping the world's free-flowing rivers. *Nature*, 569, 215–221.

Islam, Md.R., *et al.*, 2024. Reconstruction of avulsion history of the Brahmaputra River: Rare example of a giant braided river course alteration through multi-channel multi-avulsion processes. *Evolving Earth*, 2, 100034.

ISPMC, 2019a. *Long-term effects of river narrowing on water levels*. Supplementary annex F1 to main report of Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) Tranche 1, Institutional Strengthening and Project Management Consultant (ISPMC), Northwest Hydraulic Consultants and Euroconsult Mott MacDonald in association with RPMC, Deltares and CEGIS: Edmonton, Canada.

ISPMC, 2019b. *Impact of earthquake-induced sediment supply variability*. Supplementary annex F5 to main report of Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) Tranche 1, Institutional Strengthening and Project Management Consultant (ISPMC), Northwest Hydraulic Consultants and

Euroconsult Mott MacDonald in association with RPMC, Deltares and CEGIS: Edmonton, Canada.
IWM, 2019. *Brahmaputra-Jamuna River economic corridor development program*. Dhaka, Bangladesh: Institute of Water Modelling.
Jagers, H.R.A., 2001. A comparison of prediction methods for medium-term planform changes in braided rivers. *In: Proceedings 2nd IAHR Symposium on River, Coastal and Estuarine Morphodynamics*: Obihiro, Japan, 10-14 Sept. 2001, 713-722.
Klaassen, G.J., and Masselink, G., 1992. Planform changes of a braided river with fine sand as bed and bank material. *In: Proceedings Fifth International Symposium on River Sedimentation*: Karlsruhe, Germany, 459-471.
Klaassen, G.J., Mosselman, E. and Brühl, H., 1993. On the prediction of planform changes in braided sand-bed rivers. In: S.S.Y. Wang, ed. *Advances in Hydro-Science and –Engineering*. University, MS, USA: Publication of University of Mississippi, 134–146.
Klijn, F., Asselman, N., and Mosselman, E., 2019. Robust river systems: on assessing the sensitivity of embanked rivers to discharge uncertainties, exemplified for the Netherlands' main rivers. *Journal of Flood Risk Management*, 12 (Suppl. 2), e12511. doi:10.1111/jfr3.12511.
Kulnu, A.S., Hazarika, N., and Bharali, P., 2024. Evolution and morphodynamics of the large braided river Brahmaputra during the last four decades of the Quaternary epoch: a spatio-temporal assessment using geoinformatics. *International Journal of River Basin Management*, 1–19. doi:10.1080/15715124.2024.2421372.
Magherini, A., 2024. *JamUNet: predicting the morphological changes of braided sand-bed rivers with deep learning*. Thesis (MSc), Delft University of Technology: Delft, the Netherlands, October 2024.
Molinas, A., and Wu, B., 2001. Transport of sediment in large sand-bed rivers. *Journal of Hydraulic Research, IAHR*, 39 (2), 135–146.
Montgomery, D.R., *et al*., 2004. Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. *Quaternary Research*, 62, 201–207.
Morgan, J.P., and McIntire, W.G., 1959. Quaternary geology of the Bengal basin, East Pakistan and India. *Bulletin of the Geological Society of America*, 70, 319–341.
Mosselman, E., 2005. Basic equations for sediment transport in CFD for fluvial morphodynamics. *Chapter 4*. in: P.D. Bates, S.N. Lane and R.I. Ferguson, eds. *Computational Fluid Dynamics; Applications in environmental hydraulics*. Oxford: Wiley, 71–89.
Mosselman, E., 2006. Bank protection and river training along the braided Brahmaputra-Jamuna River, Bangladesh. In: G.H. Sambrook Smith, et al., ed. *Braided rivers; Process, deposits, ecology and management*. Oxford: Blackwell Publication, 277–287.
Mosselman, E., 2020. Studies on river training. *Water*, 12 (11), 3100.
Mosselman, E., Shishikura, T., and Klaassen, G.J., 2000. Effect of bank stabilization on bend scour in anabranches of braided rivers. *Physics and Chemistry of the Earth, Part B*, 25 (7-8), 699–704.
Mosselman, E., and Sloff, C.J., 2002. Effect of local scour holes on macroscale river morphology. *In*: D. Bousmar and Y. Zech, ed. *River Flow* 2002, Proceedings International Conference on Fluvial Hydraulics: Louvain-la-Neuve, Belgium, 4-6 September 2002, 767-772.
Mostafa, M.G., *et al*., 2024. Analysis of river dynamics and neotectonics of the Jamuna River using satellite and seismic data in Madarganj Upazila of Jamalpur District, Bangladesh. *Natural Hazards*, doi:10.1007/s11069-024-07085-z.
Nelson, A., Dudill, A., and Amin, M.R., 2024. *Timescales of formative fluxes and principal controls on the channel width of the Jamuna River, Bangladesh. Manuscript*.
Oberhagemann, K., Aminul Haque, A.M., and Thompson, A., 2020. A century of riverbank protection and river training in Bangladesh. *Water*, 12, 3018. doi:10.3390/w12113018.
Pangare, G., *et al*., 2021. *The restless river; Yarlung Tsangpo - Siang - Brahmaputra - Jamuna*. Washington, DC, USA: World Bank.
PIANC, 2024. *Sustainable management of the navigability of natural rivers*. Report InCom/EnviCom Working Group 236, The World Association for Waterborne Transport Infrastructure: Brussels, Belgium, June 2024, ISBN 978-2-87223-043-3.
Pickering, J.L., *et al*., 2019. Impact of glacial-lake paleofloods on valley development since glacial termination II: a conundrum of hydrology and scale for the lowstand Brahmaputra-Jamuna paleovalley system. *GSA Bulletin*, 131, 58–70.
Piégay, H., *et al*., 2005. A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. *River Research and Applications*, 21, 773–789.
Rahman, M., *et al*., 2019. *Concept note on managing Brahmaputra-Jamuna river system. Final Report*. Dhaka, Bangladesh: Bangladesh University of Engineering and Technology (BUET). September 2019.
Rashid, M.B., *et al*., 2024. Synthesis of drainage characteristics, water resources and sediment supply of the Bengal basin. *Quaternary Science Advances*, 16, 100244.
Ribberink, J.S., and Van der Sande, J.T.M., 1985. Aggradation in rivers due to overloading - analytical approaches. *Journal of Hydraulic Research*, 23 (3), 273–283.
Sarker, M.H., *et al*., 2014. Morpho-dynamics of the Brahmaputra–Jamuna River, Bangladesh. *Geomorphology*, 215, 45–59.
Sarker, M.H. and Thorne, C.R., 2006. Morphological response of the Brahmaputra-Padma-Lower Meghna river system to the Assam earthquake of 1950. In: G.H. Sambrook Smith, et al., ed. *Braided rivers; Process, deposits, ecology and management*. Oxford: Blackwell Publication, 289–310.
Sun, T., Meakin, P., and Jøssang, T., 2001. Meander migration and the lateral tilting of floodplains. *Water Resources Research*, 37 (5), 1485–1502.
Thorne, C.R., 1993. *Personal communication*. FAP22 experts' discussion workshop: Dhaka, Bangladesh, 2-4 November 1993.
Thorne, C.R., 1996. *Personal communication*. EGIS office: Dhaka, Bangladesh.
Thorne, C.R., Russell, A.P.G. and Alam, M.K., 1993. Planform pattern and channel evolution of the Brahmaputra River, Bangladesh. In: J.L. Best and C.S. Bristow, eds. *Braided rivers*. London.: Bath, 257–276.
Wang, Z. (Zhaoyin), and Liu, C. (Cheng), 2019. *Controlling the Yellow River: 2000 years of debate on control strategies*. Report, Technical Secretariat for the International Sediment Initiative, IHP, UNESCO, January 2019.