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REVIEW **Open Access**

Geomorphological processes and their connectivity in hillslope, fluvial, and coastal areas in Bangladesh: A review

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Abstract: Geomorphological knowledge is critical in understanding watershed scale surface processes, including steep mountainous areas and flat lowlands, particularly if the mid- and downstream areas are densely populated and hazard assessments are highly required. However, our knowledge about such surface processes has relatively been limited in some areas in South Asia due likely to the lack of comprehensive studies of geomorphology and related fields. This article undertakes an overview of the geomorphological processes of the disaster-prone deltaic landscape of the Ganges–Brahmaputra–Meghna (GBM), particularly focusing on fluvial processes. The area locates in the downstream of the watershed system including Himalayan Mountains and highly connected with the upper basin morphodynamics, hydrology, and sediment flux. The previous studies are summarized at different geomorphic settings concerning hillslopes, fluvial plains, and coastal areas to provide clarity about the geomorphic processes linking erosion-prone upstream source areas to deposition-dominated downstream areas. The review found that most of the geomorphic researches in Bangladesh are exploring landslide inventory and susceptibility mapping in hilly areas; river channel or riverbank shifting, riverbank erosion and accretion in fluvial environments; watershed morphometric analysis and geomorphic unit identification in plain land; and coastline shifting or coastal erosion and accretion in coastal environments at a small scale. Then, we discuss the fluvial dynamics and sediment transport of the GBM river system to address the knowledge gap in the context of deltaic plain land in Bangladesh, where upstream fluvial sedimentation processes impact the geomorphic connectivity from Himalayan to the Bay of Bengal. Although some studies on the fluvial dynamics and sediment dispersal in the upstream GBM river basin are present, the fluvial processes in the downstream domain of Bangladesh are not fully understood with a limited number of research with field-based approaches. Some future perspectives of geomorphic research in Bangladesh are then mentioned to understand better the complex geomorphological settings in the entire GBM watershed and to strengthen the existing research capacity. This review will also develop a holistic understanding of fluvial geomorphic processes of the GBM River to the policymakers and may be helpful to improve the transboundary river basin management policies or strategies.

Keywords: Ganges–Brahmaputra–Meghna (GBM), Bangladesh, Satellite remote sensing, Fluvial processes, Sediment dispersal, Landslides, Coastal erosion

1 Introduction

The Ganges–Brahmaputra–Meghna (GBM) river system is the largest delta of the world, where the Brahmaputra is known as Jamuna River, and the confluence of Ganges and Jamuna River is known as Padma River (Sarker et al. 2014). The Meghna River (upper and lower Meghna) confluences with the Padma River at its upstream and downstream. The braided Jamuna, the meandering Ganges,

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the anastomosing upper Meghna, and the anabranching lower Meghna make the river planform more diverse and complicated (Sarker et al. 2014). Geographically, the major part of the GBM basin in Bangladesh is entirely lowland, which is surrounded by India on the west, the Myanmar on the east, Shillong Plateau on the north, and Bay of Bengal on the south (Steckler et al. 2010) (Fig. 1). However, most of the rivers of Bangladesh (405 rivers including 57 transboundary rivers) are originated from the Himalayan and East Indian mountains and flow through Bangladesh into the Bay of Bengal (BWDB 2014; Dewan et al. 2017). In terms of mean annual discharge, the GBM river system is second only to the Amazon, and a major portion of this flow occurs in the summer season with immense monsoon rainfall, which causes widespread flooding in these drainage areas (Steckler et al. 2010). Therefore, the geomorphological features are changing very rapidly in downstream Bangladesh despite its remarkably flat topography due to the complex upstream fluvial process (Takagi et al. 2005). These fluvial dynamics are controlled by natural processes (discharge flow, sediment transport, debris flow, channel migration and floodplain erosion, and accretion) (Langat et al. 2019) and anthropogenic processes (dam constructions, river bank engineering, and land-use changes) (Surian and Rinaldi 2003; Wellmeyer et al. 2005; Ortega et al. 2014). The geomorphic research describes both these natural and anthropogenic factors to explain the surface process, shape and dimension, spatiotemporal variability, and evolutionary characteristics of landscapes and landforms (Pareta and Pareta 2015).

However, apart from Himalayan tributaries, numbers of tributaries from upland source areas are joining the Ganges–Brahmaputra (GB) river system and it also hosts a large number of floodplain wetland and lakes (Singh et al. 2021). Furthermore, the geomorphic diversity of river formation and processes in the Himalayan foreland and hinterland are demonstrated by the climatic diversity along the strike of the Himalaya (Sinha 2004). Because there is a close relationship among geomorphology, river

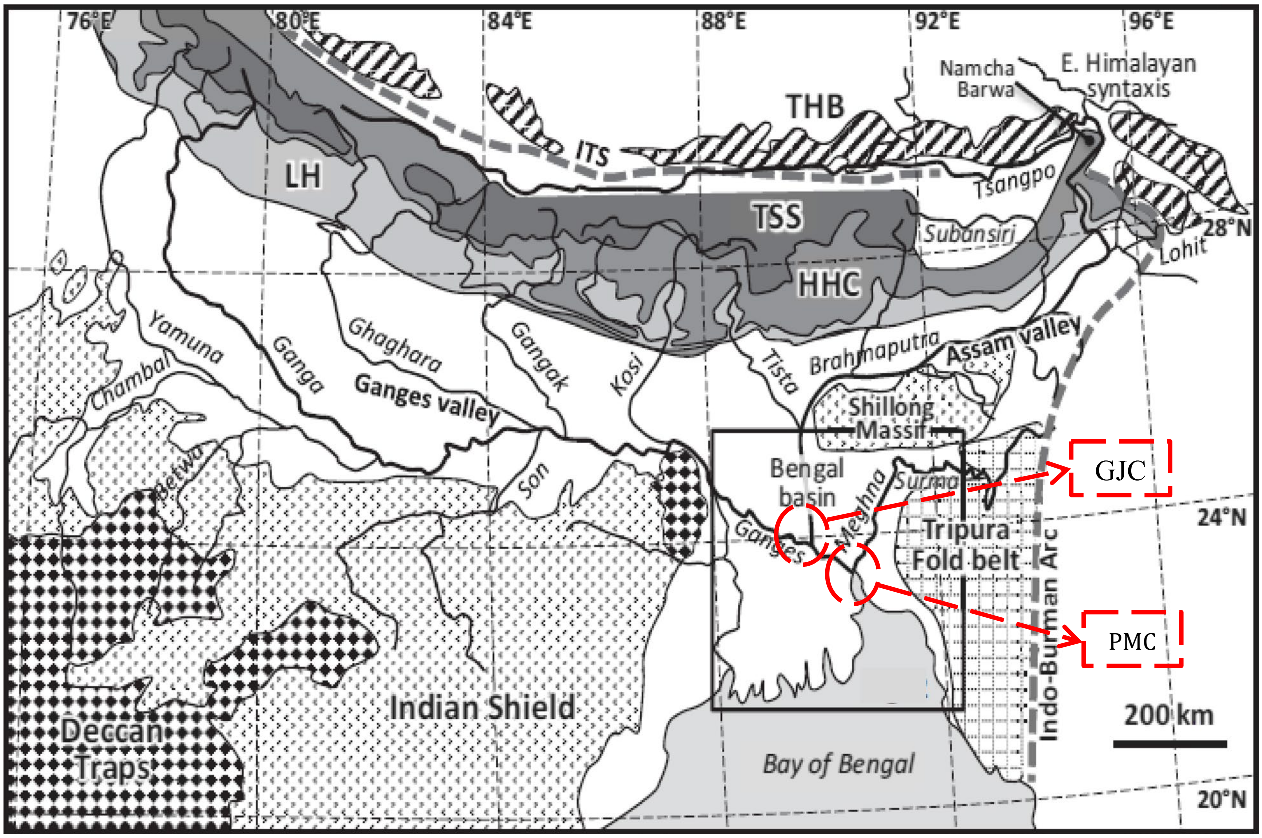

Fig. 1 Map of the Ganges–Brahmaputra–Meghna river basin representing major tributaries and sediment sources including Trans-Himalayan batholiths (THB), Tethyan Sedimentary Series (TSS), High Himalayan Crystalline Sequence (HHC), Lesser Himalayas (LH), Indus-Tsangpo suture (ITS) (after Goodbred et al. 2014). The rectangle focuses on the Bengal basin that influences the river migration and sediment dispersal across the Ganges–Brahmaputra–Meghna delta. GJC and PMC indicate the Ganges–Jamuna confluence and Padma–Meghna confluence, respectively (Gazi et al. 2020a)

engineering, hydrometeorology, and environment, the geomorphological study of the large Ganges–Brahmaputra river system is highly important to understand the process–form relationship of fluvial systems and landscape diversity. Also, an understanding of large GB river systems is critical as they support large human populations, where Ganges and Brahmaputra support a population of 400 million (Jain et al. 2012) and 83 million people (about 41% residents in Bangladesh), respectively (Mahanta et al. 2014). However, despite the enormity of the Ganges–Brahmaputra fluvial system and the general advancements in recent fluvial geomorphological studies (Oguchi et al. 2013, 2022), the hydro-geomorphic information in GBM is somewhat restricted (Ray et al. 2015; Fischer et al. 2017) and research availability has been fragmented at its downstream areas. On the other hand, significant research regarding the Ganges–Brahmaputra river hydrology, geomorphology, and sedimentology had been carried out by several researchers in India (Jain et al. 2012), covering the upper part of the Ganges–Brahmaputra basin. However, the integration of geomorphic and hydrological studies in the upstream and downstream reaches of the GBM basin has been limited.

Moreover, in the context of Bangladesh, which hosts two most diverse Ganges–Brahmaputra basins, not many studies on fluvial geomorphology and sediment dynamics have been conducted so for. Geomorphic research is still in the nascent phase in Bangladesh and previously studied by only a few researchers (Coleman 1969; Umitsu 1985, 1987, 1993; Best and Ashworth 1997; Allison et al. 1998; Ashworth et al. 2000; Islam et al. 2001; Takagi et al. 2007; Goodbred et al. 2014; Brammer 2014; Sarker et al. 2014; Dewan et al. 2017) focusing on channel diversion, erosion and accretion, sediment deposition, and few hydro-geomorphic systems. Earlier, Takagi et al. (2005) reviewed the geomorphological and geological researches of Bangladesh and tried to reflect some of the geomorphic research gap and realities and mentioned the limited scientific researchers. However, as discussed later, current geomorphic researches in downstream Bangladesh are mostly conducted at a small scale within the country. The insights obtained at small-scale studies are not sufficient to understand the large-scale landscape process (Baker 1988; Lane and Richards 1997; Jain et al. 2012). Moreover, the hydrological event that occurs in the upper part of a river basin may have a direct influence on downstream from a few to many hundreds of kilometers away (Nepal 2012; Nepal et al. 2014). Hence, the understanding of upstream–downstream linkages in hydrological processes of Ganges–Brahmaputra river basin is essential for water resources management of downstream Bangladesh.

Besides, there is an imperative need among the scientific community to understand better the geomorphic consequences of ongoing global environmental changes (Lane 2013; Knight and Harrison 2014; Harrison et al. 2019), where the mountainous landscapes including the diverse fluvial system deserve particular attention (Cienciala 2021). These realizations highlighted the importance of geomorphic analysis at the cross-country scales because the fluvial system, including sediment connectivity and sediment dynamics, of downstream Bangladesh is mostly influenced by the upper and middle Ganges–Brahmaputra system (Subramanian and Ramanathan 1996; Sinha 2004; Singh 2007). Therefore, there is a need to review the previous geomorphic studies with a holistic view of dealing with fluvial geomorphic research in downstream the deposition zone (Bangladesh) connecting the upstream Ganges–Brahmaputra basin. This sort of review study is required to find out the geomorphic research gap, to improve the understanding of geomorphic processes in complex downstream areas, and to unearth the flood-prone deltaic landscape connected with morphodynamics, hydrology, and sediment flux in the upper basins. In addition, an understanding of upstream dominated processes or events or sediment transport dynamics that shape the particular landform development of downstream areas is highly important in geomorphic science (Howard 1994; Whipple and Tucker 1999; Stark and Stark 2001). Therefore, this study may help us answer the questions in geomorphology, how the magnitude and frequency of upstream event plays a more influential role in developing geomorphic characteristics of the downstream (Wolman and Miller 1960; Rinaldo et al. 1991; Pelletier 2003).

In such a context, a large part of this work focuses on reviewing the previous geomorphic research in downstream Bangladesh. Also, this article attempts to review some of the major aspects of the Ganges–Brahmaputra fluvial system that evaluates their relevance to understand the fluvial system of downstream Bangladesh taking into consideration the geomorphological diversity of the upper Ganges–Brahmaputra river system. Some of the potential implications for future geomorphic researches concerning downstream flat alluvial Bangladesh are also discussed here that can help minimize the multitude of river basin management problems. Therefore, we present an inclusive review of the Ganges–Brahmaputra fluvial system, starting from the mountainous catchments to the deltaic plain concerning vast alluvial plain land in Bangladesh. In summary, the aim of this article is (a) to review the previous geomorphological research in Bangladesh with a focus on different geomorphic features, including landslides in hilly area, fluvial channel dynamics, plain land features, and coastal dynamics; (b) to critically analyze the fluvial dynamics and sediment pathways of active plain land Bangladesh that governs by the upper Ganges–Brahmaputra river system; and (c) to highlight some potential future geomorphic research for better understanding of the downstream geomorphic process in Bangladesh considering the recent advancement and regional studies.

2 Main text

2.1 Major geomorphic features in Bangladesh

Regarding the major geomorphic characteristics in Bangladesh, here we review geomorphic researches previously performed in the area at different scales, focusing on hillslopes, fluvial dynamics, plain land formation, and coastal dynamics.

2.1.1 Hilly area

A large variety of erosional and depositional features may be formed in mountainous and hillslope areas. The hilly or mountainous terrain is mainly found in the north and southeastern part of Bangladesh (18% of the total country area) and is mostly covered with dense vegetation (Rabby and Li 2018). The hilly regions of southeast Bangladesh (Chittagong Hill Tracts) are underlain by Surma and Tipam rocks (Brammer 1996), and the soil formation is complex and unstable (Islam et al. 2017). The young rock formation contains feldspars vulnerable to weathering (Ahmed et al. 2014), which make these regions more susceptible to landslide risks during heavy rainfall (> 40 mm/day) in the monsoon (June to October) season within a short period (2–7 days) (Khan et al. 2012; Sarker and Rashid 2013a, b). In Chittagong Hill Tract (CHT) region, rainfall-induced landslides (Khan et al. 2012) are increasing and causing death and damage to property (Ahmed and Rubel 2013; Rabby and Li 2019; Rabby et al. 2020).

Furthermore, the southeastern hilly region of Bangladesh is regarded as a high-risk zone for flash floods and landslide events associated with intense rainfalls (Ahmed and Dewan 2017; Rahman et al. 2017). Also, flash flood vulnerability studies have been carried out by Rahman and Salehin (2013) and Sarker and Rashid (2013a, b), but detailed watershed morphometric analysis has not been studied. Meanwhile, Adnan et al. (2019) assessed the flash flood susceptibility of the Karnaphuli and Sangu river basins in the southwest region with DEM-derived twenty-two morphometric parameters. The analysis revealed that more than 80% of the total area is susceptible to flash floods with moderate to a very high level of severity. On the other hand, morphometric analysis of major watersheds in the northwestern Bangladesh (Barind tract) has been carried out by Rahman et al. (2017). They found a dendritic drainage pattern with 1st to 6th stream order, moderate to a flat slope, moderate drainage density, semipermeable soil lithology, and homogenous soil texture. Similarly, small-scale morphometric analysis has been conducted by Jahan et al. (2018) in the Atrai–Sib River Basin (northern part of Bangladesh).

Moreover, the landslide scenario of this hilly region is aggravated by increased population, rapid urbanization, indiscriminate hill cutting and deforestation, and inappropriate land-use practices (Sarker and Rashid 2013a, b; BUET-JIDPUS 2015). Rabby and Li (2020) identified 730 landslides in Chittagong hilly area from January 2001 to March 2017 based on Google Earth images, field mapping, and literature search. The literature works on landslide event were collected from local newspapers, Comprehensive Disaster Management Program (CDMP) phase II-2012, records of the disaster management department, and road and highway department of the people's republic of Bangladesh. However, comprehensive identification and response to the landslide occurrence in this remote hilly area are still difficult due to its inaccessibility covered by dense forest, faster vegetation regrowth after landslide, cloudy Landsat imageries, and unavailability of airborne light detection and ranging (LiDAR) images, aerial photographs, and unmanned aerial system (UAS)-based images (Rabby and Li 2018).

Besides, Ahmed (2015) prepared landslide susceptibility mapping in one of the hilly areas of southeastern Bangladesh (Cox's Bazar) applying artificial hierarchy process (AHP), weighted linear combination (WLC), logistic regression, and multiple logistic regression techniques. Almost similar studies also have been carried out by Ahmed and Dewan (2017) and Rahman et al. (2017) in the Chittagong area of Bangladesh. Also, Rabby et al. (2020) evaluated the performance of several digital elevation models (DEMs) including global digital elevation models (GDEM) (30 m resolution), Shuttle Radar Topographic Mission (SRTM) (30–90 m), the Phased Array type L-band Synthetic Aperture Radar (PALSAR-DEM) (12.5 m) and Survey of Bangladesh (SoB) DEM (25 m) (generated from spot height) for landslide susceptibility mapping in one of the CHT region (Rangamati district) of Bangladesh. The comparative usability study of different DEMs concludes that except SoB-DEM (only source of local DEM in Bangladesh), all other global DEMs are suitable for the landslide suitability mapping in Bangladesh. The applicability of those landslide susceptibility maps to local areas in both scientific and social contexts is, however, still limited due partly to their coarse-resolution and the unavailability of field-based work on the landslides.

2.1.2 Fluvial features

2.1.2.1 Channel dynamics In geomorphological studies, river channel formation and dynamics are the foremost topics (Petts 1995). While the fluvial processes in Bangladesh connecting upstream areas are discussed in more detail in Sect. 3.1, here we summarize the overview of fluvial geomorphological studies in Bangladesh. The most comprehensive remote-sensing-based geomorphological study in Bangladesh about the Brahmaputra River channel has been conducted by Takagi et al. (2007) over the time period of 1967–2002. They separated the Brahmaputra River into four phases, namely: (a) the late 1960s to early 1970s; (b) the mid-1970s to early 1980s; (c) the mid-1980s to early 1990s; and d) the mid-1990s to early 2000s. Phase (a) and phase (b) have been regarded as transitional phases with more complex conditions, which trigger frequent large floods and may significantly change the river system. Also, a state of dynamic equilibrium has been observed from the mid-1990s to the early 2000s due to small spatial variations both in the braided belt width and in the channel width. However, based on the study of the historical evolution of the Brahmaputra–Jamuna by Coleman (1969), Sarker et al. (2014) summarized that the rate of channel (Brahmaputra–Jamuna) widening ($\sim 152\ \mathrm{my}^{-1}$) was high but the channel migration was effectively zero in last four decades (1970–2010). On the other hand, the Ganges catchment (Ganges and Padma) in Bangladesh annually receives 1200 mm of average rainfall (Sulser et al. 2010), which is one of the factors of the recurring large magnitude of seasonal floods during the monsoon period (July–October) (Gupta 1995; Kale 2003; Sharma 2005). The study of Dewan et al. (2017) concludes that the Padma (Aricha–Chandpur) experienced a total of 183 km^2 of erosion (left bank 155 km^2 and right bank 28 km^2) which led to the occurrence of many extreme floods since 1973. Furthermore, Islam (2016) analyzed the Landsat MSS 1977 (9 Feb), Landsat TM 1989 (11 Nov), and Landsat ETM+ 2000 (17 Nov) data and assessed the fluvial channel dynamics of Padma River in Northwestern Bangladesh. This study showed a remarkable change in the position of the riverbank, river channel, as well as bars, along with the geometry and morphology over 23 years (1977 to 2000). Besides, the findings suggest that the bankline of Padma River is not stable and in recent decades it can be migrated continuously toward westward (Shamsuzzaman et al. 2005; Talukder and Islam 2006).

The morphodynamics of two major confluences of Bangladesh Rivers, namely the Padma–Meghna confluence (PMC) and the Ganges–Jamuna confluence (GJC), have been studied recently by Gazi et al. (2020a) (Fig. 1). This study found that GJC moved to southwest direction and PMC moved to northwest direction over the period (1980–2019), but these directions of confluence migration were reverse before 1980s. At the same time, the width of PMC shows variation from 6.87 to 6.98 km, whereas the GJC confluence shows a decreasing trend of 8.10 to 2.80 km over the period (1972–2019). Further, Akhter et al. (2019) explore spatiotemporal changes of Teesta River channel morphology and forecast midline channel shifting in the reach over the period (1972–2017) through multi-date Landsat imageries (MSS/TM/ETM+/OLI) and SRTM-DEM (30 m) data and autoregressive integrated moving average (ARIMA) model. This study found that, like other river systems of Bangladesh, the Teesta River width is becoming narrow in recent times than earlier decades (Takagi et al. 2007; Sarker et al. 2014; Bhuiyan et al. 2015; Dewan et al. 2017). Besides, over the period (1972 to 2010) and (2010 to 2017), the Teesta channel is shifting toward the right side (0.34 km/year) and left side (−0.14 km/year), respectively. However, channel shifting rates of Teesta River are mostly affected by the temporally changing amount of sedimentation, but the spatial changes are more controlled by the differences in riverbank conditions. Further, the ARIMA model predicts the rightward direction of maximum midline channel shifting for 2017 to 2024 and leftward midline channel shifting between 2024 and 2031 because of reduced water flow at downstream of Teesta River, resulting from the construction of dams and embankments at upstream, which restricted the water flow and increased the number of bars (Ghosh 2014; Khan and Islam 2015).

2.1.2.2 Sediment dynamics The GBM river system of Bangladesh is highly prone to channel shifting, erosion, accretion, and riverine island (locally Char) development due to high sediment transport or movement process in the monsoon season (Sarker et al. 2011). However, the sediment budget of the large braided river (Jamuna) largely depends on the river's flow path along the floodplain, suspended sediment transport regime, and average sedimentation rates (Allison et al. 1998; Takagi et al. 2007). In the Ganges and Brahmaputra River, 78% of the total suspended load is from the Brahmaputra River (Islam et al. 2001), where the siltation rate has been increased in recent years (Khalil et al. 1995). Like fluvial processes, the nature of sediment dispersal in the GBM catchment is also diverse but not fully understood or studied. The sediment dispersal in GBM catchments connecting the upstream catchments to the downstream reaches in Bangladesh is further discussed based on the existing literature in Sect. 3.2.

Examples of studies of fluvial sediment transport include the work of Islam et al. (2001), who used advanced very-high-resolution radiometer (AVHRR) images of 1996 and Landsat images of 1991. This work was designed to understand the seasonal and spatial variations of suspended sediment in the Ganges and Brahmaputra Rivers in Bangladesh for both high-discharge periods (June to October) and low-discharge periods

(November to May). They found higher suspended sediment concentration (SSC) (1150 to 1375 mg/l) in the Ganges than the Brahmaputra (1000 to 1275 mg/l) in high-discharge period, whereas reverse scenario has been observed for low-discharge period. The significant fluctuations in SSC and suspended sediment load along the Ganges and Brahmaputra River courses have been attributed to riverbank erosion and accretion, as well as the aggradation of riverbeds.

Similarly, Islam et al. (2002) examined the distribution of suspended sediment through Landsat images of 1989 and 1991 in the coastal sea around the Ganges–Brahmaputra River mouth, showing that transportation and deposition of suspended sediments experience seasonal variations (SSC varies from 200 to 700 mg/l during low-discharge period and 1300–1500 mg/l during high-discharge period). They also found that the suspended sediments are accumulated on the shallow shelf (between 5 to 10 m water depths) in the low-discharge period, and on the mid-shelf (between 10 to 75 m water depths) in the high-discharge period with an average rate of 2 cm/year. However, an empirical (exponential) relationship has been found between the gradual settle down of suspended sediments in the coastal area and its lateral distance from the turbidity maximum. Moreover, annual pluvial flooding during the monsoon period (Warner et al. 2018) due to short or prolonged precipitation (Falconer et al. 2009) in the southwestern coastal region of Bangladesh has become more intense and severe because of siltation in riverbeds and encroachment of drainage channels. This southwestern coastal region mainly comprises Ganges River floodplains, Ganges tidal floodplain, and old floodplain basins (Brammer 2014). Consequently, Adnan et al. (2020) developed a sediment deposition model for southwestern coastal region of Bangladesh using flood data from Bangladesh Water Development Board (BWDB), precipitation data (1948–2012) from Bangladesh Meteorological Department, and DEM data from Advanced Land Observing Satellite (ALOS). This model predicts that the increase in land elevation could be up to 1.4 m in every 5 years, which would alleviate land subsidence and modify several geomorphological factors such as curvature, slope, aspect, and Stream Power Index (SPI). SPI is a measure of the erosive power of surface runoff, which is considered as one of the factors that determine the river channel erosion, basin-scale variability in channel processes, morphology, and sediment transport potentiality (Moore et al. 1991; Pei et al. 2010; Khosravi et al. 2016; Kaushal et al. 2020). This study reveals that the implementation of tidal river management (TRM) in southwestern Bangladesh could potentially improve the physical condition of the natural drainage basin by reducing the value of SPI, which reduces the erosion potential of the surface. Besides, the limitations of the sediment deposition model have been mentioned in this study with available experimental sedimentation data.

2.1.2.3 River bank management Generally, floods often occur due to extreme condition of climatic triggers, and their effects are also conditioned by hydrological, geomorphological, and anthropogenic factors (Adnan et al. 2020). Bangladesh is prone to multiple flood hazards due to the frequent attacks of cyclones and the physiographic settings of large plain land (Rahman and Salehin 2013). Consequently, riverbank erosion and accretion is a very common and dynamic process in the fluvial system of Bangladesh (Islam et al. 2014). A very recent study by Rashid et al. (2021) revealed that due to the route change, the Brahmaputra–Meghna in Bangladesh grabbed ~ 2817 km^2 of invaluable land resources and a newly developed $\sim$ 4563 km^2 from 1971 to 2014. The National Plan for Disaster Management (NPDM) describes that the Padma River is quite sensitive to erosion and accretion processes, significantly affecting the society and economy to hinder the further development along the riverbank areas (Islam 2000; NPDM 2006). Billah (2018) studied the Padma River erosion and accretion scenario from 1975 to 2015, finding that the total amount of riverbank erosion in the 40-year period was 49,951 ha of land (rate of 1249 ha y^{-1}) and accretion was 83,333 ha of land (rate of 2083 ha y^{-1}), also causing the riverbank shift. Furthermore, Gazi et al. (2020b) studied the erosion–accretion of Gorai–Madhumati River (a tributary of Ganges River), finding that the total river bank erosion of 80.84 km^2 and accretion of 82.9 km^2 over the years (1972–2018). The analysis also revealed that Gorai–Madhumati River experienced extreme sedimentation due to reduction in water discharge which consequently causes numerous problems in the river basin areas, and without attention and proper river management it will no longer exist with the present flowing condition. Also, the fluvial landform characterization studies of Biswas et al. (2021) depict that erosion and accretion of Madhumati River Basin (source of freshwater in southwestern hydrological region of Bangladesh) have increased during the flooding period of 1988 and 1998, and the basin boundary shifted toward east, which impacted negatively on floodplain resources, agricultural resources, and biodiversity.

A large number of people live in floodplains of Bangladesh with vulnerability to floods and river erosion, and the number of causalities due to floods has become higher than the other natural disasters (Tingsanchali and Karim 2005). In this connection, Hoque et al. (2011) evaluated the RADARSAT images of 2004 (June 5, July 24, and Sep 9) and Landsat images of 2000 (Feb 28 and Oct

25) as well as ground data for flood monitoring and mapping in the northeastern part of Bangladesh, concluding that this region is more prone to floods than the other parts of Bangladesh. They also concluded that RADARSAT data can clarify questions related to the mapping of inundation areas more clearly and quickly than the Landsat imageries, where Landsat is often unavailable due to the cloudiness in monsoon season over Bangladesh.

2.1.3 Plain land features

The northwestern part of Bangladesh has been divided geomorphologically into a) uplifted blocks of terraced land called as Barind Tract, b) Himalayan piedmont plains, c) alluvial lowland along the Brahmaputra–Jamuna River, and d) alluvial lowland along the Ganges River (Kubo 1993). On the other hand, the southwestern portion of the basin is formed by the deposition of the mainstream Ganges River and its numerous tributaries and distributaries (Alam et al. 2003; Ravenscroft 2003). Therefore, for understanding the landscape development, a comprehensive geomorphic mapping is required in plain land, which is still missing mostly for Bangladesh (Oya 1979; Mahmud et al. 2017). Nevertheless, Mahmud et al. (2017) identified major geomorphic units of the western Ganges delta and divided the geomorphic features into fluvial deltaic plain (FDP) and fluvio-tidal deltaic plain (FTDP). Also, this study depicts that elevated concentration of arsenic (As) occurs mainly in deeper FDP due to the absence of permeable layer between shallow and deep aquifer, whereas chloride concentration shows an increasing trend in groundwater from FDP to FTDP (north to south). Furthermore, geomorphological maps of Dhaka city have been prepared by Kamal and Midorikawa (2004) and Karim et al. (2019). In the northern district (Pabna) of Bangladesh, Islam et al. (2015a, b) also identified the different geomorphic units, including active channels, abandoned channels, natural levees, flood plains, flood basins, and lateral channel bars.

However, morphometric analyses are a prerequisite for delineation of potential watershed (Aher et al. 2014) and water management aspects (Malik et al. 2019) where the hydrological information is unavailable. In this regard, Arefin and Alam (2020) focused on morphometric analysis for water resource management in the Dhaka city area. Their study suggests that surface water can be extracted from a fifth-order stream and can be supplied to the domestic area after water quality treatment. Furthermore, Arefin (2020a) identified the groundwater potential zones at the drought-prone Plio-Pleistocene highland in the northern part of Bangladesh using WLC and GIS-based multi-criteria evaluations for class normalization using Saaty's AHP (Saaty 1977). This study determines clay soil regions with high slopes and roughness as low groundwater potential zones in this area. Similarly, groundwater potentiality identification and prediction studies have been conducted in two metropolitan cities of Dhaka and Chittagong by Arefin (2020b) and Akter et al. (2020), respectively.

2.1.4 Coastal features

As a transitional zone between land and water, the coastal zone is one of the most dynamic and unstable geomorphic units in Bangladesh (Minar et al. 2013; Brammer 2014). The coastal environment is governed by terrestrial and marine forces (Kabir et al. 2020), and the coastal vulnerability of Bangladesh is largely controlled by the geomorphic processes of the GBM river basins (Islam et al. 2015a, b). Also, the external forces, including water-logging, soil erosion, salinity intrusions, sea level rise, cyclone, storm surge, and tsunami, adversely affect the morphological settings of the coastal environment and negatively impact coastal area development activities (CZPo 2005; Barua et al. 2010). Ahmed et al. (2018) focused on land dynamics of the entire coastal zone (western, central, and eastern) and determined a net gain of 237 km^2 (annual average of 7.9 km^2) of land from 1985 to 2015. This study also revealed that both erosion and accretion rates are higher in the central zone compared to the western and the eastern zones of the coastal area. Shibly and Takewaka (2012) studied the morphological changes along the western–central coast in 1989–2010, which obtains a large volume of discharge from the GBM river system through Sibsha, Pasur, and Baleswar River (Allison et al. 2003; Iftekhar and Islam 2004). They found that the western–central shoreline in 2000–2010 was more stable than its previous decade (1989–2000). They also found that the mangrove-covered area is changing more significantly compared to the flat sandy beach, in contrast to the thought that mangrove stabilizes the land. Also, Alam and Uddin (2013) mentioned that, over the last 34 years (1977–2010), the coastal areas and the offshore Island of Bangladesh gained 139 km^2 of land from continuous erosion and accretion process. However, based on the Coastal Vulnerability Index (CVI) methods (Thieler and Hammar-Klose 1999; Doukakis 2005; Diez et al. 2007): Islam et al. (2015a, b) showed that the western coast of Char Fasson and the northern and southwestern coast of Bhola Island (Bhola Sadar) are the most vulnerable coastal regions of Bangladesh. Likewise, Miah et al. (2020) also applied CVI (Szlafsztein and Sterr 2007, 2010; Mahapatra et al. 2014) by combining both the Physical Vulnerability Index and Social Vulnerability Index for the southeastern coast (Chittagong district) of Bangladesh. This study revealed 43% of the total southeastern coastal area as highly vulnerable to flooding, storm surges, and cyclones, and the rural area is more prone to disaster impacts than the urban area.

2.2 Fluvial processes of GBM from upstream to downstream

As reviewed above, among various geomorphic features, fluvial processes are the major factor forming the landscape of Bangladesh. Here, we review the studies on fluvial processes in further details. For the understanding of the downstream fluvial processes, fluvio-sediment dynamics of the upstream of GBM catchments are crucial and we first summarize river hydrology, river system, sediment transport, and discharge therein. Then, we discuss geomorphic knowledge gap regarding the connectivity between the upstream and downstream domains and motivate larger-scale (beyond country scale) fluvial geomorphic studies.

2.2.1 Fluvial processes of Bangladesh in response to upstream GB

2.2.1.1 River hydrology The annual flow pattern of large Himalayan (Ganges and Brahmaputra) and peninsular river (Mahanadi, Tapi, Kaveri, etc.) system suggests that these rivers are mostly characterized by non-monsoonal low or no flow (7–8 months), common monsoon flow (4–5 months), and occasional large magnitude flow during monsoon (Kale 2005). Except for the catchment of the Brahmaputra in Tibet, all other drainage basins of the GBM River falls within the monsoonal regime of South and Southeast Asia, where rainfall pattern varies significantly, for example 743 mm/y in Tibetan Plateau, 1349 mm/y in Himalayan belt, and 2354 mm/y in floodplain (Immerzeel 2008). Consequently, 80–95% of water discharge is observed in the Ganges and Brahmaputra during southwest monsoon (June to November) (Subramanian and Ramanathan 1996), which led to a concurrent increase in sediment discharge (Mukherjee et al. 2009). For instance, the Ganges, Brahmaputra, and Meghna discharges 70,792,116 kg/s, over 70,792,116 kg/s and 14,158,423 kg/s, respectively, at lower reaches during monsoon flood season (Coleman 1969). The monsoonal dominancy of annual discharge at the GB basin has also been mentioned in earlier studies of Kale (2005) and Mahanta et al. (2014). The monsoon-dominated rainfall and melting of the Himalayan snow from the upper GB river system cause a large magnitude of floods in downstream Bangladesh and therefore impact fluvial dynamics, but this process remains unclear or not studied (Fig. 2).

2.2.1.2 GBM River system dynamics The drainage network map of Ganges–Brahmaputra–Meghna River (Fig. 3) shows that several tributaries of the Ganges (Yamuna, Ghagra, Gandak, Kosi, Chambal, Son, etc.) and the Brahmaputra are draining toward the Bay of Bengal (BoB) forming the major delta in the Bengal basin (Subramanian and Ramanathan 1996; Sinha 2004). The drainage development of the Ganges–Brahmaputra is generally derived from several factors such as tectonics and climatic patterns in the lowland area (Gupta 1997; Friend et al.1999). The longitudinal profile of the Ganges shows

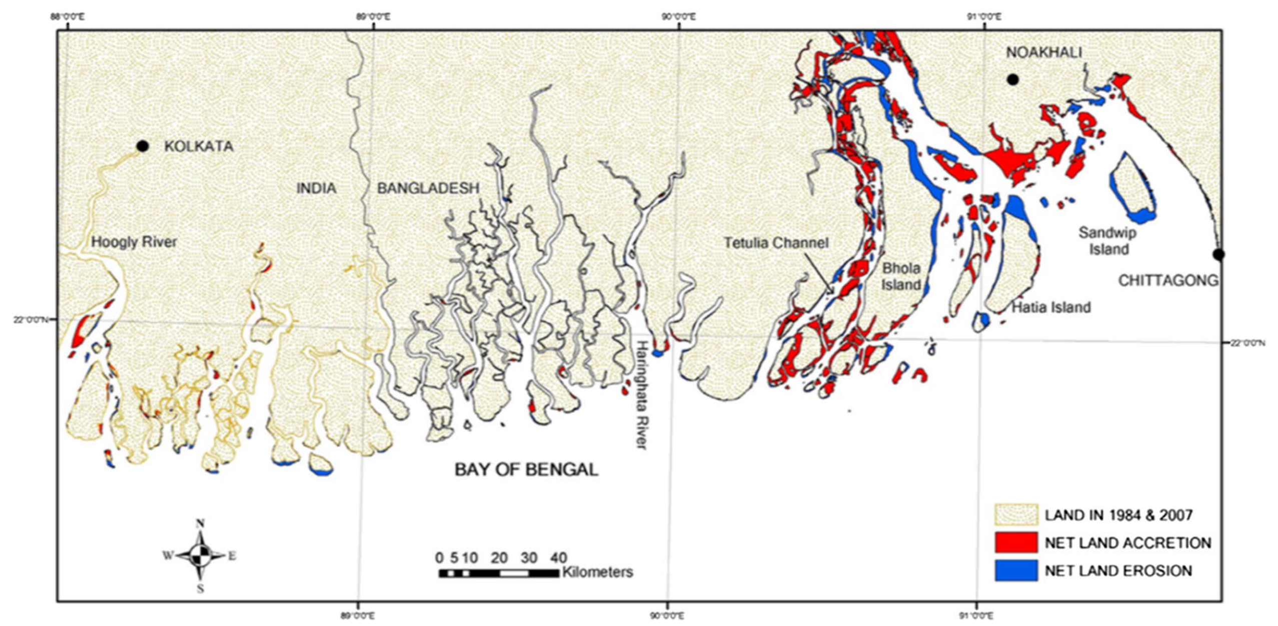

Fig. 2 Gains and losses of land on the Brahmaputra–Ganges–Meghna delta front in 1984–2007 (after Brammer 2014)

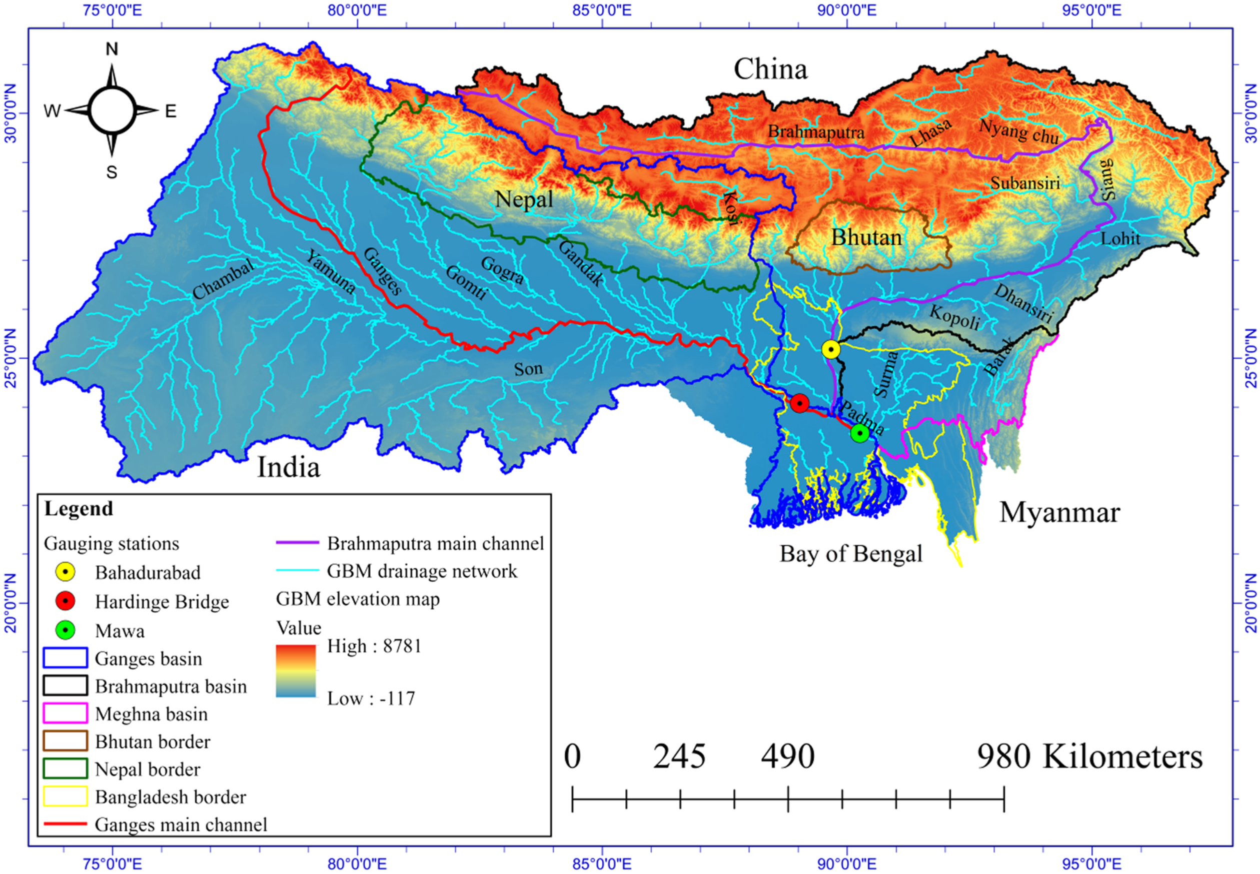

Fig. 3 GBM river basin elevation and drainage network. The elevation is prepared based on NASA-DEM (30 m resolution). The yellow, red, and green circles denote the in situ gauging stations for discharge estimations

a sharp change in a gradient from steeper mountains to the gentler downstream plains (Fig. 4). The Brahmaputra River profile shows relatively low gradient in the upstream reach but drastically drops to the Assam plains (Gupta 2007; Mahanta et al. 2014; Ray et al. 2015), resulting in abundant sediment deposition and formation of braided channels in the downstream reach (Pangare et al. 2021). Overall, the deviations of the Ganges–Brahmaputra River longitudinal profile are related to the Himalayan tectonics, water discharges, and sediment load characteristics of these basins (Seeber and Gornitz 1983; Goswami 1985; Gupta 2007).

In the southeastern center of the Tibetan Plateau, glaciers feed the Tsangpo-Brahmaputra River, and the increased rates of snow and glacial melt are likely to increase summer flows in the downstream Brahmaputra (Immerzeel 2008; Bolch et al. 2010). Remarkably, the behavior of the Himalayan rivers (intense slope failure, landslide, and debris flow resulting from earthquake or intense rainfall) changes as they enter into the Indus–Ganga–Brahmaputra plain by shifting river course and changing morphology and bedforms due to heavy discharge and sediment load (Goswami 1985; Sinha and Friend 1994; Kale 2005). For instance, the 1897 and 1950 earthquakes impacted Brahmaputra River sediment supply (bed load increases) and channel morphology in Assam, India (Coleman 1969). An integrated drainage network has been formed at Brahmaputra River in India (Assam), where braided channels composed of mainly fine sand with various dimensions of rivers are developed, including straight, sinuous, meandering, tortuous, braided, anastomosing, anabranching, and reticulate features (Sarma 2005). After crossing India (Assam), the Brahmaputra enters Bangladesh (about 47,000 km^2 of total 580,000 km^2 drainage basin) after traveling 220 km from the Indian border along the northern area (Kurigram) through Himalayan flows (Sarma 2005; Sarker et al. 2014) and started to avulse linearly into the southward passage from the beginning of the eighteenth century (Bandyopadhyay et al. 2021). The bed scours depths of up to 40 m with a combined channel pattern of braided and anastomosing makes the Jamuna extremely

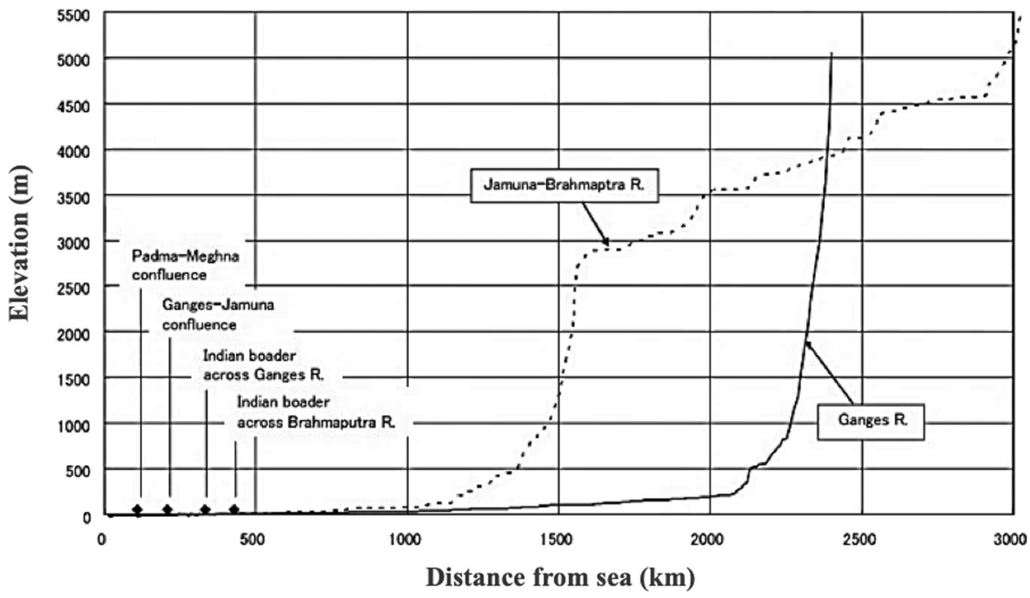

Fig. 4 Longitudinal profiles of Ganges–Brahmaputra–Meghna showing the entire flow path. Compiled from several sources (JICA report 2005; Quamruzzaman et al. 2008)

dynamic and critical in devising engineering strategies, which implies the necessity of proper interpretation of ancient sediments and sea level changes (Bristow 1987; Best and Ashworth 1997; Thorne et al. 1993; Peters 1993; Ashworth et al. 2000). In addition, the Jamuna is continually changing due to rapid rates of bar migration, bank erosion (up to 1 km per year), and shifting of braid belts (usually up to 5 km wide) (Klaassen and Masselink 1992; Hossain 1993; Ashworth and Lewin 2012). Apart from natural processes, the Brahmaputra–Jamuna river is continuously facing various anthropogenic stressors like frequent land-use change, channelization, and regulations of normal river flow (Gupta et al. 2019) (i.e., Teesta barrage at its upstream, Jamuna multipurpose bridge, etc.), which emphasizes the implementation of sustainable solutions (Pradhan et al. 2021). For instance, the present site of the Jamuna multipurpose bridge was selected based on the geomorphological study conducted by Oya (1979).

On the other hand, draining from southern Tibetan uplift, the Ganges main channel had major movements in the historical period (after 1857), which caused highly irregular shapes of valley (Hedge et al. 1989). The Ganges in India traverses through rugged mountains to flat alluvial plains, crossing various climatic zones with extensive erosional processes (Sinha 2004; Jain et al. 2012). Nevertheless, regarding the source area (mountains catchments), alluvial plains, and deltaic plain, the Ganges river system shows unique fluvial processes where upstream flows control the landform development (Sinha 2004). From two major branches of the Ganges (Bhagirathi and Padma in India), the Padma flows southeastward along the India–Bangladesh border and then takes eastward flow through Bangladesh (about 34,188 km^2 of total 980,000 km^2 drainage basin) to join with the Brahmaputra or Jamuna, forming the largest Ganges–Brahmaputra delta in the world (Islam et al. 1999). The bankline migration of the Ganges/Padma in Bangladesh shows that both the left and right banks do not follow the same direction (rightward) and are highly dependent on the localized factors and sedimentary features. Moreover, the Ganges is affected by human intervention, including the construction of Farakka Barrage by India in 1975 at 18 km upstream from the India–Bangladesh border, and is responsible for erosion both in India and in Bangladesh (Sarker 2004; Rahman and Rahaman 2018).

At the downstream GB basin, the Meghna has combined flow of Ganges–Brahmaputra/Jamuna into the Bay of Bengal, forming lower Bengal delta near Bangladesh coast. Hence, Bangladesh's coastal area has become more diverse and dynamic than it generally appears where rapid geomorphological changes are occurring in the Meghna estuary (Allison 1998a, b; Brammer 2014). The Meghna catchments experienced a net gain of 451 km^2 with a growth rate of 19.6 km^2/y over 1984–2007. Noticeably, despite gaining land in Meghna estuary, it showed considerable land losses along the east of Sandwip Island, north of Hatia, and northeast of Bhola Island, whereas erosion is gradually increasing eastward in the southwestern coast along the Hooghly estuary in India (Fig. 2) (Allison 1998a, b; Brammer 2014).

Fluvial studies of the upper Ganges in India had been thoroughly reviewed and updated by Sinha (2004) and Jain et al. (2012), respectively, whereas the fluvial research of the lower GBM (Bangladesh) regarding the causes of anomalous channel behavior, riverbank migration, erosion and accretion, sedimentation in tidal floodplains and coastal process is not fully investigated or conducted at small scale or has spare literature (as mentioned in Sect. 4).

2.2.2 Fluvial sediment dynamics of Bangladesh in response to upstream GB

2.2.2.1 GBM sediment production The Trans-Himalayan batholiths, Tethyan Sedimentary Series, High Himalayan Crystalline Sequence, Lesser Himalayas, the Deccan Traps, the Shillong Massif, and Tripura fold belt are the source areas of GBM basin sediment, where the Indus-Tsangpo suture is connecting the sediment sources between Asia and India (Galy et al. 2010; Goodbred et al. 2014) (Fig. 1). Through the Indus-Tsangpo suture, the Brahmaputra traverse via Namcha Barwa syntaxis which encompasses only 4% of Brahmaputra's catchment but contributes about 45 ± 15% of sediment load (Singh and France-Lanord 2002; Garzanti et al. 2004; Stewart et al. 2008; Goodbred et al. 2014). Beneath the syntaxis (drops for 2 km elevation), the Brahmaputra flows into low-lying Assam Valley and Himalayan foreland, where the rest of the load is supplied from the Himalayan tributaries (Goodbred et al. 2014).

On the other hand, after originating along the Tibetan border in north India, the Ganges headwater drained large areas of Himalayan front slope and its entry point to Bengal basin, the Ganges derived 90 ± 5% sediment load from the high Himalayan areas (Wasson 2003; Singh et al. 2008; Lupker et al. 2012; Goodbred et al. 2014). Furthermore, the erosion intensity and sediment sources of upstream Himalayan Ganges catchments had been mapped in several studies (Narayan et al. 1983; Subramanian and Ramanathan 1996; Sinha et al. 2002; Vaidyanathan et al. 2002). The different estimates of suspended sediment load from the GB river system have been documented in various studies and are summarized in Table 1. The sedimentation in the downstream reaches of the GB is related to the lowland fluvial processes and aggradation/degradational behavior of midstream alluvial reaches, which may create such variability of sediment load estimations among the researchers (Goswami 1985; Islam et al. 1999; Jain et al. 2012). Nevertheless, the sediment load values comprise significant uncertainties, and exact values cannot be determined despite continuous decadal observations due to wide diurnal, seasonal, and annual variations in the sediment transport capacity of the GB Rivers (Subramanian and Ramanathan 1996; Islam et al. 1999). The Brahmaputra has higher suspended load than the Ganges (Coleman 1969; Milliman and Meade 1983; Islam et al. 1999), because the eastern Himalayan range has higher precipitation and higher erosion rates than the western part (Galy and France-Lenord 2001). Nevertheless, according to various estimates of sediment transport in several studies, it can be mentioned that the aggradation or degradation processes in the mid-downstream alluvial reaches are quite complicated, causing significant variability of deposition rates in the downstream reaches (Jain et al. 2012).

Table 1 Estimates of suspended sediment load (million tons/year) of the Ganges–Brahmaputra River from different studies (updated after Islam et al. 1999)

Suspended sediment of Ganges River		Suspended sediment of Brahmaputra River	
(Mt/y)	**(Reference)**	**(Mt/y)**	**(Reference)**
375	NEDECO (1967)	750	NEDECO (1967)
1600	Holeman (1968)	800	Holeman (1968)
485	Coleman (1969)	617	Coleman (1969)
520	BWDB (1972)	541	BWDB (1972)
680	Milliman and Meade (1983)	1157	Milliman and Meade (1983)
328*	Abbas and Subramanian (1984)	402*	Goswami (1985)
729*	Abbas and Subramanian (1984)	710*	Subramanian (1987)
403	Singh (1988)	650	Hossain (1992)
316	Islam et al. (1999)	721	Islam et al. (1999)
550	CEGIS (2010)	590	CEGIS (2010)

NEDECO The Netherlands Engineering Consultants Ltd., *CEGIS* The Center for Environmental and Geographic Information Services

*Estimated at Indian reach and rest of the estimate stands for Bangladesh

2.2.2.2 Sediment discharge The GBM river system in combination discharges 1×10^{12} m^3 of water and 1×10^9 t of sediment per year to the Bay of Bengal (Goodbred and Kuehl 1999; Wasson 2003; Akter et al. 2016), of which 440×10^6 t/y and 540×10^6 t/y is contributed by Ganges and Brahmaputra, respectively (Milliman and Syvitski 1992). According to Islam et al. (1999), the Ganges and the Brahmaputra in combination carried 1037 million tons/y of sediment into Bangladesh, of which about 525 million tons/y (51%) reaches the sea, 289 million tons/y (28%) deposited on land to balance the basin subsidence, and the remaining 223 million tons/y (21%) is deposited on the river beds. In turn, about 49% of the total sediment budget is trapped or deposited before the coastal region (Islam et al. 1999). This contributes to the intense monsoon flooding that facilitates the longer overbank flow (Ashworth and Lewin 2012). The suspended sediment load estimation of the Ganges, Brahmaputra, and combined GB River was derived from the gauging data from the Hardinge Bridge, Bahadurabad, and Mawa stations (160 km downstream of Hardinge Bridge), respectively (Fig. 3). The aggradation of the Brahmaputra River (> 14.7 mm/year) suggests that around 30–40% of GB sediment flux is estimated to be deposited in Bangladesh deltaic region before being transferred into the ocean (Goodbred and Kuehl 1999; Jain et al. 2012). Moreover, the Ganges River beds are aggrading about 3.9 cmy^{-1}, 2.5 times higher than the Brahmaputra in Bangladesh (Islam et al. 1999).

Recently, Dietrich et al. (2020) provides a first-order estimate of the yearly discharge of elements in the suspended sediment load to the BoB by the Ganges–Brahmaputra based on the dataset of Garzanti et al. (2011) that includes grain size, suspended sediment concentration, mineralogy, and element concentrations for suspended load samples collected at 0 to 24 m depths from locations in the Ganges (downstream of Hardinge Bridge), Brahmaputra (Sirajganj to Jamuna Bridge), and Padma (near Mawa) rivers during the monsoon season. This study shows that, on average, the GBM system transport 0.7×10^9 tons/y sediments to the BoB, contributing ~ 5% of the global riverine discharge of solid-phase elements. These elements are relatively enriched in Hf (hafnium), Zr (zirconium), Th (thorium), REEs (rare earth elements), Sn (tin), and Bi (bismuth), largely reflecting the nature of Himalayan source material. Moreover, it should be mentioned that future anthropogenic changes such as large-scale damming projects could significantly alter the delivery of sediment into the BoB, i.e., completion of the proposed National River Linking Project (NRLP) in India may reduce the annual suspended sediment load in the Ganges and Brahmaputra by 39–75% and 9–25%, respectively (Higgins et al. 2018). Also, future climate change scenarios projected the increase in sediment discharge by 34–37% in the Ganges and 52–60% in the Brahmaputra by the end of the twenty-first century (Darby et al. 2015).

Unfortunately, the quantitative sediment budget studies of Islam et al. (1999) and Dietrich et al. (2020) do not consider the sedimentation at lower Meghna (after Padma River between Mawa and the mouth of these rivers), which is naturally dynamic and also altered by various anthropogenic stressors. Also, the mechanism or process of sediment dispersal including sediment connectivity pattern from the erosion-dominated upper GB to the lower Meghna (tide and wave dominated) has not been fully mentioned or understood. At the lower GB, the main channel of the Meghna River, which is composed of braided and meandering channel sediments from the Brahmaputra/Jamuna and Ganges (Mukherjee et al. 2009), contributes significantly to the stratigraphy of main delta downstream (Goodbred et al. 2014). Furthermore, the downstream delta is also dominated by tidal wave rather than runoff where Meghna–Surma (both fluvial and tidal) sediments contribute considerably (Islam et al. 2002). The sediment load of GBM delta is geochemically distinct, which makes this a potential location to unravel the dynamics of multiple fluvial systems interacting within a tectonically active basin (Goodbred et al. 2014; Li et al. 2020). Thus, the suspended load data, aggradation scenario, and projected sediment load estimation suggest disconnected or partially connected Himalayan foreland, where the eroded sediments from Himalayan could not reach the downstream sink area. Therefore, the geomorphic connectivity from the Himalayan to the BoB might be affected by sediment trapping before the mouth of these GBM rivers. Hence, the basin-wide integrated investigation from source to the mouth focusing on the lower Meghna reach may provide insights into quantifying annual sediment released by the GBM river system into the BoB. A conceptual diagram that shows the geomorphic connectivity impeded by sediment trapping within the GBM basin from the existing studies is presented in Fig. 5.

As noted, the GBM river supports over 150 million people at downstream reaches (Bangladesh), which are vulnerable to the impacts of relative sea level rise, climate changes, annual floods, shifts in land use, and water management (Brammer 2014; Goodbred et al. 2014). Accordingly, based on the findings by Miah (1988) and Brammer (1990a, b a, b), it was reported that more than 56.9% of total areas of Bangladesh are flooded annually due to monsoon rainfalls and increased water discharge from the upstream Himalayan area (BGS/DPHE 2001). Also, Coleman (1969) estimated that during flood events, sand bars migrated at a rate of 300–450 m/day or even up to 600 m/day, and channel area increased about 300% in the Brahmaputra. Besides, Singh et al. (2007) reported that floods in the Ganges are also strongly influenced by high sediment discharge and water volume, and this has also been mentioned by the other studies (Wallick et al. 2007; Ahmed and Fawzi 2011; Yao et al. 2011; Rozo et al. 2014). It is obvious that sustainable river management is demanded and challenged in the large GBM river, which tends to flow in international basins (Gupta 2007; Rasul 2014). However, the lack of publicly available long-term and spatially distributed hydrological data (discharge and river characteristics) at a basin-wide scale limits the understanding of hydrological and geomorphological processes of the GBM river basin (Kibler et al. 2014), which is a prerequisite for sustainable water resource management in this downstream region (Fischer et al. 2017). Being a downstream country, Bangladesh faces

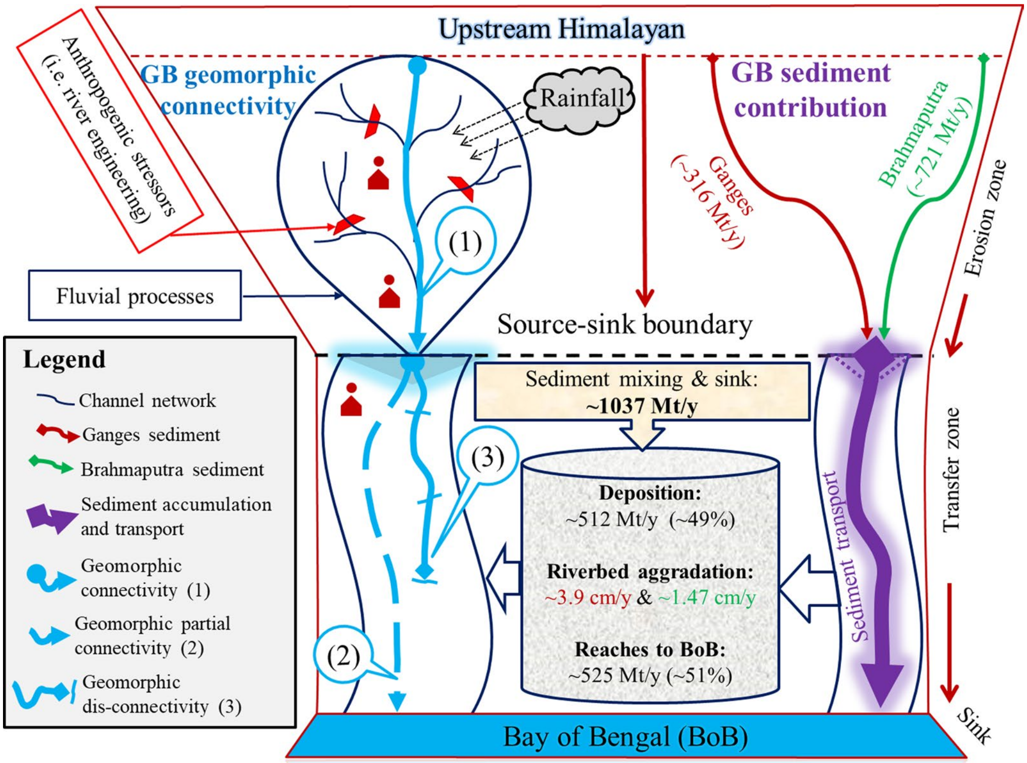

Fig. 5 A conceptual diagram showing the geomorphic connectivity from the Himalayan upstream to the BoB based on the existing literature (Goodbred and Kuehl 1999; Islam et al. 1999, 2001; Wasson 2003; Garzanti et al. 2011; Jain et al. 2012; Dietrich et al. 2020). On the right side, sediment contribution from upstream two major basins is shown. On the left side, the connected (1) and partially connected (2) or disconnected (3) geomorphic systems are visualized from source to sink areas. The fluvial sedimentation processes (i.e., excessive sediment sequestering, riverbed aggradation) and anthropogenic stressors (i.e., river engineering, barrage, and dam construction) may change the geomorphic connectivity in the GBM river system. The altering geomorphic connectivity from connected to partially connected or disconnected, impeded by sediment trapping, may significantly impact the GBM river's hydro-geomorphic system. Mt/y denotes the million tons per year

many challenges in coping with altering geomorphic characteristics of the large GBM river basin and is often dictated by decisions taken outside its border. Hence, the relevant case studies of geomorphic research in Bangladesh and subsequent discussion on large-scale fluvial sedimentation on the GBM river system will enhance our understanding, which may be helpful to improve the government policies or strategies regarding integrated river basin management more sustainably. Technical challenges related to river management may arise from a lack of scientific understanding of river basins or imperfect engineering skills to manage according to that understanding (Stanley and Boulton 2000). The existing policies, plans, guidelines, and laws related to the integrated water resources management (IWRM) in Bangladesh also emphasize the understanding of the geomorphic process in GBM for sustainable development (Alam and Quevauviller 2014). Hence, the understandings of the fluvial geomorphic processes of upstream dominated large GBM river basins at a regional scale is essential to enhance the transboundary cooperation among the basin sharing countries like China, Nepal, Bhutan, and India.

However, the different case studies of fluvial geomorphic research at the downstream Ganges–Brahmaputra (Bangladesh) presented here do not involve a full potentiality of remote sensing techniques or tools in fluvial geomorphology. Therefore, applying the advanced remote sensing techniques and field-based approaches to fluvial research (e.g., Oguchi et al. 2022) in the future may provide a new dimension of fluvial geomorphic research in the hazard-prone deltaic landscape of Bangladesh. Also, our study is limited by collecting the estimates of suspended load at the different reaches of the Ganges–Brahmaputra river basin, which does not describe the sampling procedure and methods of suspended load calculation of each study mentioned in Table 1. Therefore, clarifying different methodologies of suspended load estimation may be necessary to understand better the large variations of suspended load estimations among the researchers and the sediment budget of the

Ganges–Brahmaputra river basin from the Himalayan to the Bay of Bengal.

2.3 Future perspective of geomorphic research in Bangladesh

Modern quantitative geomorphological researches on hillslope, glacial, fluvial, and coastal processes have been significantly benefited from the availability of medium-to-high-resolution (10–90 m cell size) DEMs (e.g., SRTM, ASTER G-DEM, TanDEM-X) and satellite images (e.g., Landsat, MODIS, and Sentinel 1–3) at regional and global scales for free or at a low cost (Oguchi and Wasklewicz 2011; Bishop 2013; Hackney and Clayton 2015; Otto et al. 2018; Oguchi et al. 2022). Although it is beyond the scope of this article to give a full overview of potential applications and improvements of geomorphic research considering the availability of remote sensing techniques and tools, here we explore some research gaps between recent advancement of geomorphological researches and earlier geomorphic studies of Bangladesh and provide future perspectives on the better understandings of the geomorphic processes in the context of the upper Ganges–Brahmaputra dominated Bangladesh.

2.3.1 Mountain areas

Notably, there has been an exponential growth of scientific research on mountain and hillslope environments in recent decades (Stoffel and Marston 2013; Slaymaker and Embleton-Hamann 2018; Carrión-Mero et al. 2021). Landslide susceptibility mapping is one of the major topics frequently assessed in mountainous and hilly areas. Hence, the landslide susceptibility mapping based on quantum particle swamp optimization (QPSO)–alternating decision tree (ADTree) algorithm can be a promising tool for managing landslide disaster in complex mountainous terrain, successfully applied in Sikkim Himalayan (Islam et al. 2021). Although some studies on landslide susceptibility mapping or modeling have been carried out in hilly (CHT) areas of Bangladesh (Ahmed et al. 2014; Ahmed and Dewan 2017; Rahman et al. 2017; Rabby and Li 2020; Abedin et al. 2020), those approaches based on airborne LiDAR, Synthetic Aperture Radar (SAR), and UAS data are mostly missing. The use of such advanced remote sensing datasets with a high resolution or accuracy should benefit the improved assessments of mountain hazards at a local scale. Therefore, it is anticipated to perform remote sensing-based geomorphic research on hilly region and steep slopes. The development of open access database of such remote-sensing datasets will contribute to establish a landslide early-warning system to protect the landslide vulnerable community of the CHT region.

2.3.2 Fluvial environments

After analyzing the fluvial processes of the Indian part of the Ganges–Brahmaputra delta, Subramanian and Ramanathan (1996) and Rudra (2014) mentioned the unavailability of time-series data in the upper GBM catchments and had some limitations. For instance, the work of Rudra (2014) was criticized and rectified by Bandyopadhyay et al. (2015) regarding the delineation of the Bengal basin, deltaic evolution, and discharge data for a better understanding of the fluvial geomorphic processes. However, the studies about the fluvial channel dynamics concerning Bangladesh have been started after 1990s and most of the geospatial studies have been dealing with river channel shifting (Sarker et al. 2014; Islam 2016; Dewan et al. 2017; Akhter et al. 2019; Gazi et al. 2020a), riverbank line shifting, riverbank erosion, and accretion (Billah 2018; Gazi et al. 2020b; Biswas et al. 2021). Accordingly, the research on the formation of an alluvial channel, causes of channel migration, anthropogenic impacts on fluvial system, and processes of anomalous channel variations at the downstream GBM River is still sparse or even missing. Further extensive studies are therefore required to understand better the fluvial settings considering the upstream to downstream hydrogeomorphic connectivity. Besides, the encouragement for fluvial geomorphic research in this understudied region can be taken from fluvial research advancement mentioned by Stott (2013), Wohl (2014), Piégay et al. (2015), and Oguchi et al. (2022). Hence, it is necessary to extend the geospatial research on the fluvial channel dynamics and connectivity, especially with a detailed river basin morphometric analysis at various spatiotemporal scales for predicting the morphological changes along the GBM basin. For example, hotspot zonation of riverbank erosion could be assessed with advanced techniques in the downstream Bangladesh.

On the other hand, the advancement in the application of remote sensing and GIS for riverbank management, including flood monitoring and risk assessment, has significantly facilitated in the last two decades (Sanyal and Lu 2004). Also, the use of satellite data for flood forecasting and monitoring is more frequent in developed countries than in the developing country like Bangladesh, where the geospatial data usability largely depends on the availability of cloud-free open access data. Nevertheless, in Bangladesh, most of the riverbank management studies are confined to post-flood monitoring (Hoque et al. 2011), flood susceptibility mapping (Rahman and Salehin 2013; Sarker and Rashid 2013a, b; Adnan et al. 2019; Sarkar et al. 2022), flood inundation mapping, and some small-scale watershed morphometric studies (Rahaman et al. 2017; Jahan et al. 2018). Consequently, a detailed hydro-geomorphological study of the major watershed floodplain at different spatial and temporal scales is required to make some meaningful flood hazard maps, prediction of extreme flood effects, flood forecasting, and warning based on watershed morphometric analysis and damage assessment in Bangladesh.

Furthermore, the large discharge and heavy sediment load affect the unstable conditions of the Ganges–Brahmaputra–Meghna Rivers, where channels are constantly migrating. However, despite the high possibilities of sediment disasters, only a few studies have been conducted considering the mechanisms of fluvial sediment transport and dynamics in the active downstream GBM basins. Some of the studies are linked to the distribution of suspended sediment concentration at a small scale in Bangladesh (Islam et al. 1999, 2001, 2002; Adnan et al. 2020). It should be noted that fluvial sediments are transported to Bangladesh from upstream source areas, and therefore studies on sediment dynamics need to describe the sediment connectivity and transportation pathways at a watershed scale. Researches on sediment connectivity and hydrological connectivity are growing rapidly in different hydro-geomorphic setting across the world at various spatial and temporal scales, which includes 26 different countries including the Ganges basin in India (Cavalli et al. 2013; Najafi et al. 2021; Mishra et al. 2019; Swarnkar et al. 2020). However, such studies have not been carried out yet in the downstream basins in Bangladesh, which is a sink area connected to the large upstream basins of the Ganges–Brahmaputra river system and highly prone to repeated sediment disasters. Despite the significance of the entire Ganges–Brahmaputra river system, modeling of the basin-scale sediment dynamics based on climate change scenarios, connecting the upper (China, Nepal, Bhutan, and India) and lower (Bangladesh) Ganges–Brahmaputra basins, has been limited (Khan et al. 2018). Therefore, it is obligatory to extend the geomorphic studies, specifically on sediment yield estimation, sediment budgeting, rainfall–runoff relationship, sediment connectivity, and sediment transport mechanisms connecting upstream erosion zone to the downstream deposition zone in Bangladesh. Geospatial modeling of sediment dynamics for the downstream GBM river basin based on the rapidly changing river morphology is also necessary to facilitate the research findings for disaster countermeasures.

2.3.3 Plain land and coastal areas

Although comprehensive geomorphic mapping is essential for landscape development and urban development, this important section is mostly ignored for the national development program of Bangladesh. Most of the plain land geomorphic studies in Bangladesh have been related to geomorphic mapping or identification of geomorphic units (Kamal and Midorikawa 2004; Islam et al. 2015a, b; Mahmud et al. 2017; Karim et al. 2019; Arefin and Alam 2020) and identification of groundwater potential zones (Arefin 2020a, 2020b; Akter et al. 2020), but their accuracy and precision have been somewhat limited. Therefore, comprehensive geomorphic studies of active plain land are required for proper landscape assessment and management in the densely populated areas in Bangladesh, where the framework of Thorne (2002) can be considered as a blueprint for geomorphic studies of large rivers like the Ganges and Brahmaputra.

The ununiformed sea level rise along the coast due to high sediment dispersal from the GBM river system makes the delta system more complex and vulnerable (Islam 2011; Rashid et al. 2013; Sarwar 2013; Karan 2015). Nevertheless, the coastal geomorphology of Bangladesh is poorly understood, where most of the coastal geomorphic studies are restricted to shoreline shifting (Shibly and Takewaka 2012; Islam et al. 2013; Kabir et al. 2020), coastal erosion and accretion (Rahman 2012; Alam and Uddin 2013; Sarker et al. 2013; Sarwar and Woodroffe 2013; Hussain et al. 2014), and morphological studies (Islam et al. 2015a, b; Miah et al. 2020) at small scale. Hereafter, further research is obligatory considering the long-term changes in the sediment supply from the GBM basin, associating the coastal morphological changes and relative sea level rise throughout the Bangladesh coast, which is critical to protect about 35 million people therein (Ahmad 2019). For this purpose, some coastal geomorphological research trends and challenges mentioned in French and Burningham (2009) can be considered as well for further improvement in coastal geomorphic research in Bangladesh.

2.3.4 General plain land

The above-mentioned earlier geomorphic researches provide some understandings of the evolution pattern of landforms, channel diversion, discharge variability, and sediment estimation at a country scale, but geomorphic studies at larger spatiotemporal scales have been limited in Bangladesh. Also, the causes of discharge (water and sediment) variability patterns, aggradation, deposition, upstream to downstream sediment connectivity patterns, and human-induced perturbation on river geomorphology have not been mentioned or studied clearly. Furthermore, the projection of future behavior of river formation at different spatiotemporal scales based on fluvial geomorphology, hydrology, and meteorology does not exist in these areas, but these are important for understanding the watershed-scale landscape development and the sustainability of the river basin management.

3 Conclusions

Although the review of earlier geomorphic studies provided here generally focuses on some significant knowledge and research gaps in one country (Bangladesh), we propose the necessity of exploring the wider area studies on fluvio-geomorphic and sedimentation processes in the entire GBM basin, from the upstream erosion prone zone (China, Nepal, Bhutan, and India) to downstream deposition zone (Bangladesh). The bankline migration, human interventions, and tidal processes in the Ganges; avulsion, sedimentation, erosion and accretion, and river channel dimensions in the Brahmaputra; shoreline shifting, erosion, and migration of the Ganges–Brahmaputra confluence have often been investigated at a small scale (country scale). However, the aggradation in the Ganges floodplain and retention of suspended sediment within the Brahmaputra channel are impacted by the upstream fluvio-sedimentation processes of the GBM river system, where the geomorphic connectivity from Himalayan to the Bay of Bengal is affected by sediment trapping before the mouth of the GBM rivers. Therefore, integrated regional research or basin-wide studies are required for comprehensive understanding of the fluvial processes and sediment dispersal mechanisms from upstream to downstream GBM concerning Bangladesh. In particular, the advanced remote sensing techniques (such as UAS imagery, LiDAR) for geomorphological research, which are encouragingly used in neighboring countries like China (Le Heron et al. 2019), India (Ramsankaran et al. 2020; Dhote et al. 2022), Bhutan (Dunning et al. 2009; Tempa et al. 2021), Nepal (Immerzeel et al. 2014; Kraaijenbrink et al. 2016; Van Woerkom et al. 2019), Pakistan (Khan et al. 2021), and in other parts of the worlds (Śledź et al. 2021), will improve the understandings of landscape evolution and fluvial dynamics not only in the upper Ganges–Brahmaputra but also the entire watershed scale including the downstream reaches in Bangladesh.

In summary, the literature review and discussion presented here provide very first step toward developing a detailed and documented understanding of the fluvio-geomorphic dynamics in the GBM River. We conclude that the fluvial geomorphic research at different spatial and temporal scales is a prerequisite for a large-scale basin management which is still missing here, for which the advancement from the present geomorphic research aptitude is necessary to solve a wide range of problems related to sustainable river basin management and disaster risk reduction. Also, the government policymaker can get a comprehensive idea from the subsequent discussion on the fluvial geomorphic research scale (borderless or basin-wide scale) and improve their policies or strategies accordingly to focus more on transboundary bilateral and multilateral collaboration (i.e., in situ gauging data sharing) with upstream countries like China, Nepal, Bhutan, and India.

Abbreviations

ADTree: Alternating decision tree; AHP: Artificial hierarchy process; ALOS: Advanced Land Observing Satellite; ARIMA: Autoregressive integrated moving average; AVHRR: Advanced very-high-resolution radiometer; BoB: Bay of Bengal; BWDB: Bangladesh Water Development Board; CHT: Chittagong Hill Tracts; CDMP: Comprehensive Disaster Management Program; CVI: Coastal Vulnerability Index; DEM: Digital elevation model; FDP: Fluvial deltaic plain; FTDP: Fluvio-tidal deltaic plain; GB: Ganges–Brahmaputra; GBM: Ganges–Brahmaputra–Meghna; GDEM: Global digital elevation models; GJC: Ganges–Jamuna confluence; HHC: High Himalayan Crystalline Sequence; ITS: Indus–Tsangpo suture; IWRM: Integrated Water Resources Management; LH: Lesser Himalayas; LiDAR: Light detection and ranging; NPDM: National Plan for Disaster Management; PALSAR: Phased array-type L-band synthetic aperture radar; PMC: Padma–Meghna confluence; QPSO: Quantum particle swamp optimization; REEs: Rare earth elements; SAR: Synthetic aperture radar; SoB: Survey of Bangladesh; SPI: Stream Power Index; SSC: Suspended sediment concentration; SRTM: Shuttle Radar Topographic Mission; TRM: Tidal river management; THB: Trans-Himalayan batholiths; TSS: Tethyan Sedimentary Series; UAS: Unmanned aerial system; WLC: Weighted linear combination.

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Author contributions

RF proposed the topic, collected the references, and drafted the manuscript. YH drafted the manuscript as the corresponding author. All authors read and approved the final manuscript.

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