Geomorphic change in the Ganges–Brahmaputra–Meghna delta

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Abstract | More than 70% of large deltas are under threat from rising sea levels, subsidence and anthropogenic interferences, including the Ganges–Brahmaputra–Meghna (GBM) delta, the Earth's largest and most populous delta system. The dynamic geomorphology of this delta is often overlooked in assessments of its vulnerability; consequently, development plans and previous management investments have been undermined by unanticipated geomorphic responses. In this Review, we describe GBM delta dynamics, examining these changes through the Drivers–Pressures–States–Impacts–Responses framework. Since the early Holocene, the GBM delta has evolved in response to a combination of tectonics, geology, changing river discharge and sea level rise, but the dynamics observed today are driven by a complex interplay of anthropogenic interferences and natural background processes. Contemporary geomorphic processes such as shoreline change, channel migration, sedimentation and subsidence can increase flooding and erosion, impacting biodiversity, ground and water contamination and local community livelihoods. Continued human disturbances to the GBM delta, such as curtailing sediment supplies, modifying channels and changing land use, could have a more direct influence on the future geomorphic balance of the delta than anthropogenic climate change and sea level rise. In order to contribute to long-term delta sustainability, adaptation responses must therefore be informed by an understanding of geomorphic processes, requiring increased transdisciplinary research on future delta dynamics at centennial timescales and collaboration across all governing bodies and stakeholders.

Deltas are some of the world's most critical human-nature systems. They provide diverse ecosystem services, including highly fertile soils, fisheries and potential for aquaculture, and act as hubs for international trade. Consequently, more than 500 million people live in these landforms globally[1,2]. However, deltas are growing hotspots of vulnerability to environmental change, with more than 70% of large deltas under threat from a combination of rising sea levels, subsidence and anthropogenic sediment trapping[1–3]. The sustained delivery of sediment, and its effective dispersal across the delta, is the only natural balancing control for offsetting relative sea level rise[4–6].

Although geomorphologists have been warning about the importance of sediment flux to deltaic systems for decades[1,3,4,7], human alterations to sediment balances have intensified[8]. Land use changes within upstream catchments and on deltas typically enhance local erosion and sediment flux, but this increase has been more than offset by the growing retention of water and sediment in upstream reservoirs, and by the construction of levees and embankments that inhibit coastal and overbank sedimentation[9]. The socio-economic future of these deltas, in the face of population growth and climate change, is therefore inevitably linked with their environmental well-being and geomorphic balance[3,9].

The largest and most populous delta system in the world is the Ganges–Brahmaputra–Meghna (GBM) delta, located in Bangladesh and West Bengal, India (FIG. 1). This delta covers an area of approximately 100,000 km^2 and hosts more than 170 million people[10–14]. The Ganges and Brahmaputra rivers drain approximately 75% of the Himalayan mountain range[15], resulting in more than 1 billion tonnes (BT) of sediment delivered to the delta annually[15–18]. As a result of this high sediment input meeting with tidal forces at the coast[19], the GBM estuary is characterized by erosion and accretion on the scale of several thousands of hectares of land every year[17]. Nevertheless, there is little monitoring of water flows and sediment transport, or understanding of subsidence and erosional processes within the delta[20]. Difficulty in tackling the diversity and complexity of such geomorphic dynamics has led to erroneous conclusions about how deltas function[21] and how they should be managed. Large-scale human interventions have often been implemented in unsustainable ways,

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Key points

- The interplay between long-term tectonic and eustatic sea level changes, sudden earthquake perturbances and large-scale man-made management schemes in the Ganges–Brahmaputra–Meghna (GBM) delta are the key drivers that shaped its evolution.
- This review provides a spatial representation of the sediment budget, which is necessary for delta management decisions, including the potential for harnessing natural sedimentation processes to enhance land generation.
- Mapping the spatio-temporal extent of documented geomorphic processes revealed gaps in understanding at the centennial scales and into the future, which are both critical to delta management decisions, as most infrastructures are expected to be effective for up to 100 years into the future.
- Only 40% of the 427 reviewed publications assess geomorphic processes as interconnected, potentially resulting in a fragmented understanding of dynamics.
- Geomorphic processes are mostly absent from models of flooding and water security in the GBM delta. These omissions undermine the validity of longer-term projections and call into question the appropriateness of management decisions that are based upon these models.
- Anthropogenic disturbances could have a more direct influence on the future geomorphic balance of the GBM delta than climate change and sea level rise.

resulting in a burden of costs (such as in environmental restoration)[22–24]. The future sustainability of deltas therefore requires a systems-scale understanding of their morphodynamic response to environmental and anthropogenic change[17,25,26].

In this Review, the Drivers–Pressures–States–Impacts–Responses (DPSIR) framework[27,28] is applied to bring together the existing knowledge of geomorphic dynamics in the GBM system (see Supplementary information for data and methods). With this analytical framework, we examine the interlinked relationships between social and environmental factors, and synthesize 427 peer-reviewed studies (FIG. 2; Supplementary data). The results provide a basis for informing new conceptual frameworks, modelling efforts and field studies aiming to incorporate geomorphology into human–water systems. This goal is identified as a priority research area for the GBM delta by the national Bangladesh Delta Plan (BDP) 2100 (REF.[29]) — the delta's main long-term plan that integrates all delta-related sector plans and policies[29]. Finally, existing knowledge gaps are presented and challenges and future research directions outlined.

Natural drivers

The Bengal Basin — which hosts the GBM delta — results from the ongoing collision between the Indian, Eurasian and Sunda plates[30–33] (FIG. 3). After the Younger Dryas (~12,000 years BP), strengthened monsoon precipitation increased river discharge and sediment supply, which were both considerably greater than rates observed today[9,31,34–36]. The balance between high sediment input from the rivers and rapidly rising sea level efficiently trapped riverine sediments and constructed a thick deltaic sequence[31]. During the mid-Holocene (after ~7,000 years BP), the rate of eustatic sea level rise slowed by an order of magnitude compared with the early Holocene[37–39]. The reduced rate of sea level rise facilitated the deltaic shift from an aggradational to a progradational phase, advancing the eastern portions of the subaerial delta 100 km into the sea and building a subaqueous delta plain 200 km across the shelf[9,37,39,40]. The Ganges, Brahmaputra and Meghna rivers deposited ~8,500 km^3 of sediment within the Bengal Basin over the entire Holocene[38], facilitating the shift to a progradational delta several thousand years earlier than otherwise expected[31].

Throughout the Holocene, the Brahmaputra river channel has periodically avulsed between two main courses on the eastern and western sides of the Madhupur Tract (FIG. 1) approximately every 2,000–3,000 years[36,38,41]. The last avulsion into the Jamuna river valley (thereafter named the Jamuna River) occurred sometime between 1776 and 1830 (REFS[32,36,38,41–43]), which is when the Ganges and Brahmaputra rivers first met. There are different ideas as to what drove the latest avulsion. The severe earthquakes of 1762 and 1782 are thought to have caused a vertical displacement of the Madhupur Terrace, which could have caused the river to abruptly shift to the Jamuna valley[34,43]. Contrastingly, upstream switches in the Teesta River could have caused the avulsion[32], or merely river capture into an old river course[44]. Regardless of the exact trigger for the last avulsion, the aggradation of the braid-belt led to periodic autogenic shifts of the Brahmaputra channel[15,37,38,45], driven by the abundance of sediment from the Himalayas and sustained eustatic sea level rise[36,41] (FIG. 3). This periodic switching resulted in cycles of extensive downstream delta building and rapid deposition and fan building within the Sylhet Basin[40,45–47] (FIG. 1). During the periods when the Brahmaputra was flowing to the east of the Madhupur Tract, for instance from ~7,000 to ~5,500 years BP, the coastline was seriously starved of sediment and moved 140 km inland in the eastern part of the delta and 80 km in the western part[46].

During the Holocene, the main branch of the Ganges river (which used to flow into the sea in the current location of the Bhagirathi–Hooghly River) progressively migrated eastwards[34,36,38]. This migration was predominantly driven by an eastward-tilted topographic gradient during the time that the Brahmaputra was infilling the subsiding Sylhet Basin (FIGS 1,3). Such shifting river courses change the distribution of sediment and produce new sediment-starved areas, prone to erosion and relative sea level rise[48].

Currently, more than 31,000 km^2 of former deltaic plains of the Ganges in the south-western region of Bangladesh are maintained only through ephemeral distributary channels[18,32,49]. In these regions with little direct fluvial input, the strength of the flood and ebb tides is the key driver in determining the location and distribution for sediment build-up[17,41], stabilizing the delta's morphology at the landscape scale[18,34]. The flood-dominant asymmetry in tidal currents drives a net onshore transport of sediment, enabling accretion rates in the western delta as high as 1–2 cm per year during the monsoon season[50–52]. This strong tidal influence has led to the classification of the GBM delta as tide-dominated, with tidal ranges between 3 m and 6 m, and extending over 100 km inland[11,53] (FIG. 1).

Anthropogenic pressures

During the last century, large-scale artificial changes such as river diversions, upstream dams, excavation of canals, land reclamation projects and the polderization

Aggradational
Increased land elevation due to the deposition of sediment.

Progradational
Growth of land further out into the sea.

Subaerial delta
The deltaic plains above the low-tide level.

Subaqueous delta
The deltaic plains that lie below low-tide level and extend seaward.

Avulsed
The rapid creation of a new river channel, and abandonment of the former river channel.

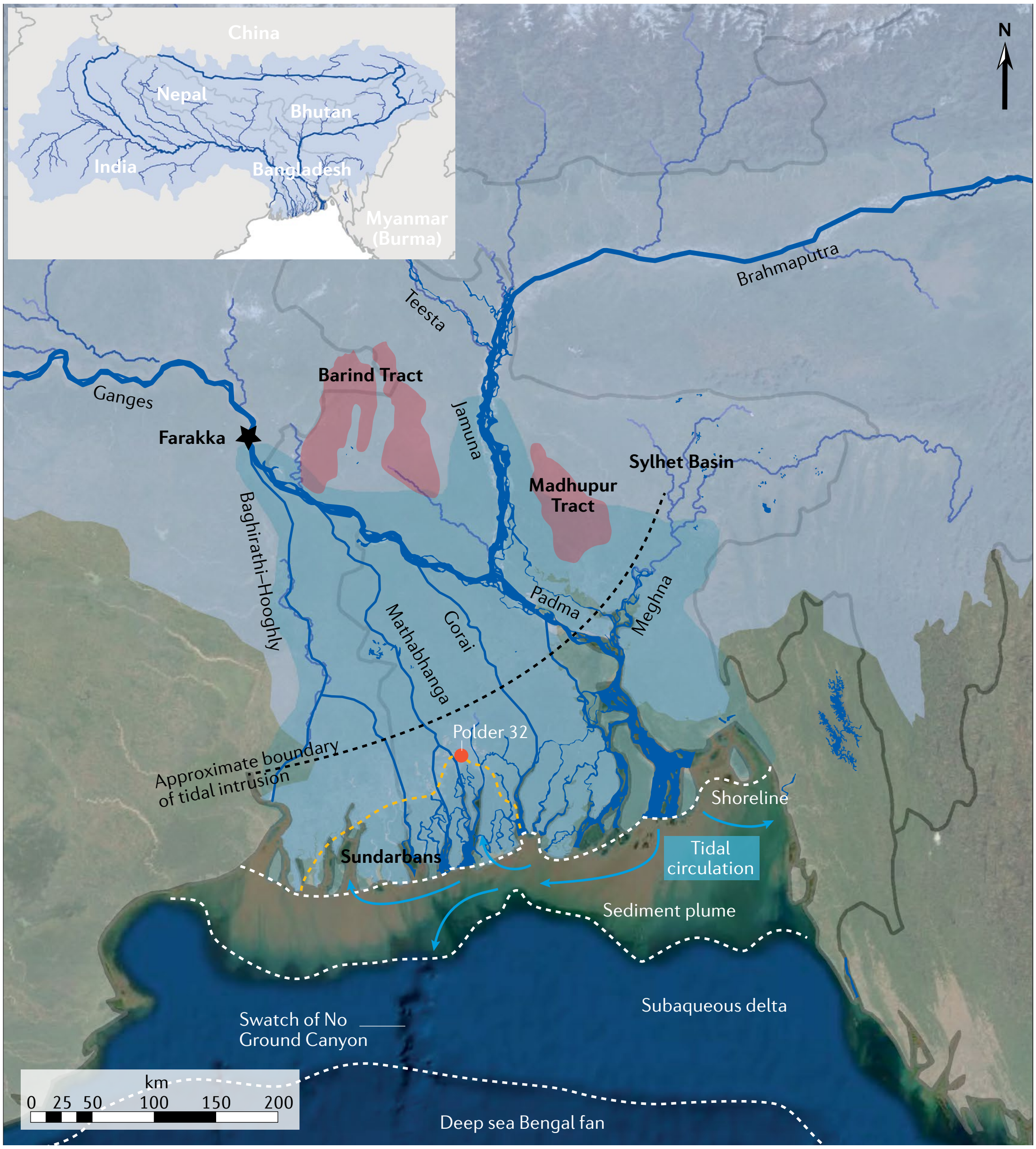


Fig. 1 | **Location of the Ganges–Brahmaputra–Meghna delta.** Geographical locations of main river channels, regions, geological features and tidal circulation patterns. Tidal intrusion boundary and circulation patterns from Wilson and Goodbred[18]. Light blue shading shows the Ganges–Brahmaputra–Meghna (GBM) watershed, whereas blue shading shows outline of the delta from Tessler et al.[13]. Base map sourced from Esri, DigitalGlobe, GeoEye, Earthstar Geographics, SNES/Airbus DS, US Department of Agriculture (USDA), US Geological Survey (USGS), AeroGRIC, IGN (the French national mapping, survey and forestry agency) and the geographic information system (GIS) user community.

(embanking) of the coastal zone[41] have disrupted the morphological equilibrium of the delta[54] (FIG. 3). In 1975, India commissioned a barrage on the main Ganges river at Farakka (FIG. 1) to divert approximately 60% of the dry-season flow towards the Bhagirathi–Hooghly River to make the Kolkata Port navigable[55–57]. This controlled hydro-geomorphological regime has dramatically altered natural processes in the south-west Ganges-dependent region, changing channel dynamics and resulting channel planforms and geometries[58–60]. Along the Bhagirathi–Hooghly River, bank erosion used to occur predominantly during the monsoon months; however, since the construction of the Barrage, the river has received higher freshwater discharge and reduced sediment flux, which has caused riverbank erosion to occur year-round[59].

The Gorai River (FIG. 1), the main distributary of the Ganges flowing to south-west Bangladesh, has seen a notable increase in siltation due to reduced river capacity to carry sediment[56,61,62], as the majority of dry-season flow has been diverted to the Bhagirathi–Hooghly River. In some areas along the Gorai River, this siltation has led to the development of charlands. The upstream reaches of the Mathabhanga River have completely dried up.

Siltation
Increased concentrations of suspended sediments and accumulation of fine sediments within river channels.

Charlands
Sand bars emerging in river channels or riverbanks as a result of sediment accretion.

Polders
Low-lying land enclosed by embankments, providing protection from storm surges and salinity intrusion.

This reduced freshwater flow has not only altered the geomorphic behaviour of the Ganges downstream of the barrage but also caused dry-season salinity in the south-west of Bangladesh to increase by an order of magnitude[56,62], which has impacted the state of the Sundarban mangrove forest ecosystem and local livelihoods[61,63]. The reduced dry-season flow in the Ganges has also altered groundwater recharge and resulted in microclimatic and agroecological changes along the lower Ganges river[64].

In addition, to further enhance the growth of land in the Meghna Estuary, land reclamation projects and cross-dams were implemented in the 1950s, and in the 1960s–1980s. The coastal region of Bangladesh was embanked to form 139 polders as part of the Coastal Embankment Project (CEP) with the aim to protect coastal communities from flooding and salinity intrusion and boost agricultural productivity and food security[11,65,66]. An increase in agricultural productivity was evident for 10–15 years, but since the 1980s the polders have become a source of major environmental concern[67]. The rivers have been disconnected from their floodplains, preventing tidal and fluvial sediment from infilling the embanked land[8,11]. This disconnection has not only lowered the relative elevation of the deltaic floodplains but also exacerbated the silting up of channels and increased sediment deposition further into the bay[8,17,41,54,56,68]. The deltaic dynamics at present are therefore a complex interplay of background natural responses to long-term change, and shorter-term responses to considerable anthropogenic activities[69].

Changing geomorphic states

The predominant geomorphic states that respond to these natural drivers and anthropogenic pressures are the amount of fluvial sediment reaching the delta, how the channels of the major rivers migrate to distribute that sediment, deltaic subsidence and the shifting patterns of the delta front. These processes are discussed in this section.

Fluvial sediment budget. Sediment budget calculations identify a delta system's sources and sinks of sediment, and the net accumulation of sediment in deltaic landforms[52,70]. Despite the acknowledged importance of sediment influx, there are considerable discrepancies in

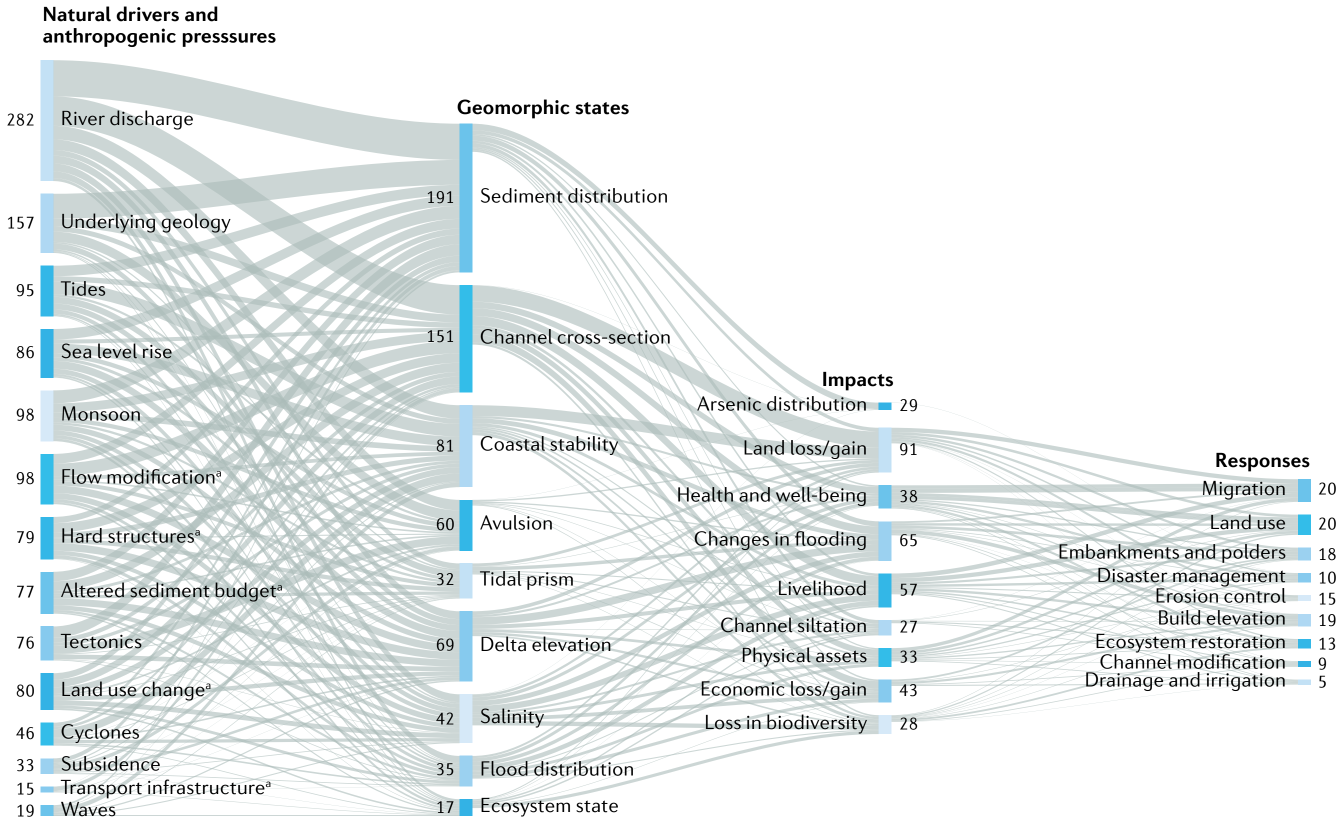


Fig. 2 | **Distribution of geomorphic studies assessing different components of the DPSIR framework.** A clear focus on the natural drivers of geomorphic change in previous studies is evident, with substantially fewer studies assessing how these changes translate into impacts upon the environment and society, and possible responses. Numbers illustrate the number of studies per topic, and width of the connections represents the number of studies assessing each interaction. Diagram shows all linkages covered in the literature; if a study covers more than one linkage, it is represented multiple times in the schematic. As an example, Bomer et al.[50] assessed delta elevation and the tidal prism as their predominant geomorphic states. Their study analysed changes in those states as a result of sea level rise, subsidence and tides as the natural drivers, as well as hard structures, flow modifications and an altered sediment budget as the human pressures. In this diagram, this study would be represented as individual chords for each of those interactions. For the purpose of the diagram, natural drivers and human pressures are grouped together as the processes that drive geomorphic change in the delta. [a]Human pressures rather than natural drivers. Note, colours improve readability but have no specific meaning. DPSIR, Drivers–Pressures–States–Impacts–Responses.

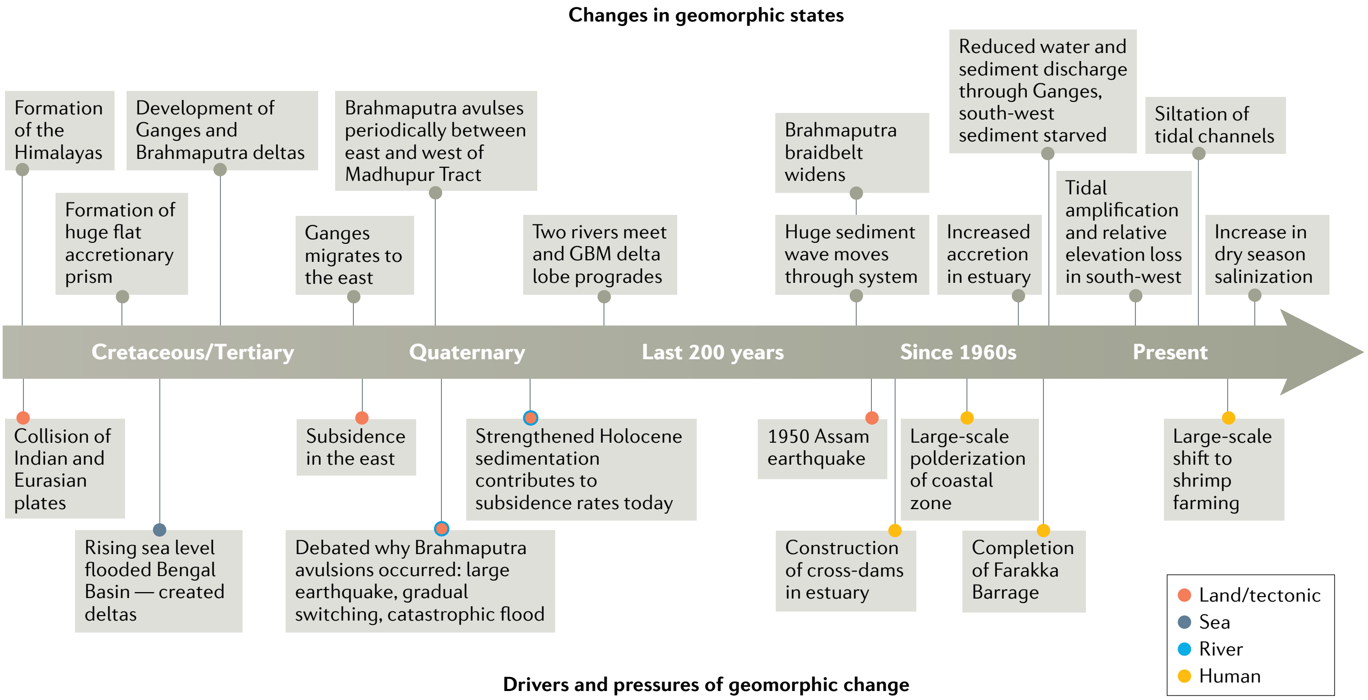


Fig. 3 | **Timeline of geomorphic evolution of the Ganges–Brahmaputra–Meghna delta.** Key geomorphic changes observed (along the top) and the predominant drivers and pressures that caused these changes (along the bottom). Historical changes were mainly driven by the interplay between tectonics and eustatic sea level changes, whereas in recent times, changes have been a more complex response to long-term natural drivers and shorter-term anthropogenic influences. Driving factors are categorized into land/tectonic, sea, river and/or human-induced. GBM, Ganges–Brahmaputra–Meghna.

our understanding of fluvial sediment budgets in many deltaic systems, including the GBM delta (see Table 3 in Supplementary information). Estimates of sediment influx to the system range between 599 and 2,400 million tonnes (MT) per year[5,71], which can be separated into components from the Ganges (260–680 MT per year) and the Brahmaputra (390–1,160 MT per year)[5]. This wide range in estimates of sediment influx can be ascribed to different measurement techniques, and assessments being undertaken over different time frames and in different locations[5]. For instance, the sediment load of the Ganges river varied from 155 to 863 MT per year during the period 1979–1995 (REF.[72]).

Despite the high uncertainty regarding sediment influx, the value of 1 BT per year is most commonly used in assessments and planning documents across Bangladesh today. This estimate originated from Coleman[42] in 1969 and was made from gauging stations more than 300 km inland of the coast with no systematic tracking of this material downstream[73]. With the exception of a few models[2,74], the majority of flood modelling and vulnerability studies adopt an annual sediment input of 1 BT, a unit that is both constant and uniform across the delta. These assumptions are fundamental suppositions that lead to the subsequent assumption that geomorphic processes and channel capacities are static and homogeneous[75,76], a problematic notion that is common across delta systems worldwide. When accounting for upstream interceptions and diversions, the sediment influx might be as little as 50% of the widely cited 1 BT per year[5,74], ranging between 150 and 590 MT per year for the Ganges and between 315 and 615 MT per year for the Brahmaputra[5]. Despite assertions of declining fluvial sediment load, the GBM coast, at present, continues to support net land growth[16,17]. This current net growth reiterates the importance of the tides in bringing material from offshore, enabling the delta to continue to maintain its geomorphic balance[18,50–52].

The spatial representation of the sediment budget and fluxes for the GBM system (FIG. 4) demonstrates the most up-to-date consensus on where sediment is coming from and where it is delivered to. Approximately one third of the annual sediment discharged by the rivers is sequestered within the floodplain and delta plain, either through direct fluvial deposition or tidal pumping, whereas the remaining load appears to be apportioned between the prograding subaqueous delta and the deep-sea Bengal fan via the nearshore Swatch of No Ground canyon system[17,18,73,77]. This spatial information is critical for sediment management decisions, including the widely discussed potential for tapping into these natural sedimentation processes to enhance land generation[73].

Channel migration. After the Brahmaputra's avulsion into the Jamuna valley, it was a single-thread meandering river, only widening and metamorphosizing into a braided channel between 1914 and 1953 (REFS[36,78]). The gradual westward migration of the Jamuna River has been recorded at rates that vary between 28 m per year[78] and 90 m per year[79]. Since the mid-1970s, the westward

Fig. 4 | **Sediment budget in the Ganges–Brahmaputra–Meghna delta system.** Sources and sinks based on literature values[52,73,77,183–185]. Numbers represent percentage distributions of sediment entering (red) and leaving (orange) the delta, and dotted blue line represents the approximate location where the delta receives 100% of its sediment before depositing it downstream.

migration of the centre line slowed and has now almost stopped, but the river's right bank continued to migrate an average of 60 m to the west, dramatically increasing the width of the first-order channel across the whole river[78,80]. The widening is hypothesized to be triggered by an increase in bedload deposition within the channel, reducing the channel depth and enhancing bar development, caused by widespread landslides from the 1950 Assam earthquake just upstream of the delta[31,36].

Over the same time period, the Padma River (FIG. 1) is morphologically dynamic in response to the massive flow of freshwater and sediment from the Jamuna[69] — from 1973 to 2011, the Padma experienced a total loss of land of 163 km^2 (REF.[69]). Despite such high erosion rates, the river also accreted new land at rates of 16.1 km^2 per year between 1988 and 2017, equivalent to 467 km^2 of newly created land over the 30-year period[81]. Further downstream, the Lower Meghna River's right bank is eroding at a 34% higher rate than the left bank, forcing the river to migrate westwards, doubling in width between 1988 and 2017 (REF.[82]). This westward migration of the Lower Meghna River has been linked to the active tectonic setting of the area, combined with periodic shifts in volumes of water and sediment coming through the system[82]. It is speculated that the substantial widening is caused by higher sediment loads from the Jamuna River (due to the Assam earthquake) being deposited on the river bed, combined with reduced water discharge from the Ganges (due to the construction of the Farakka Barrage), which together have reduced the overall depth and carrying capacity of the Lower Meghna River.

Subsidence. Subsidence is the norm in deltas, caused by multiple natural drivers such as isostatic adjustments, sediment compaction and changes in sediment distribution patterns. However, it can be locally and regionally exacerbated by anthropogenic activities including changes in farming practices, changes in coastal management, deforestation and groundwater extraction[12]. Often, publications report one value of subsidence for the entire GBM delta (for example, 18 mm per year[21]); however, subsidence in the GBM delta is neither spatially uniform nor temporally constant. Subsidence rates of between −1.1 mm (uplift) and 43.8 mm over the last 1,000 years have been recorded across the delta, with a mean of 5.6 mm per year for the whole delta, based on 205 individual point measurements[12] (FIG. 5).

The long-term and deep background subsidence is widespread but spatially variable, progressively increasing from 0 to 4 mm away from the hinge zone towards the coast[37–39,46,83] (FIG. 5). This seaward gradient of subsidence could be related to either tectonic processes, flexural and viscoelastic dynamics or sediment compaction, or a combination of these[39]. These ongoing background subsidence rates also vary seasonally; approximately 100 giga tonnes (GT) of water is stored in Bangladesh's floodplains, soils and groundwater during a typical monsoon season, which can cause an elastic deformation of the lithosphere and vertical motions of up to 6 cm[84]. These types of natural subsidence rates are expected to continue in parts of the delta, irrespective of human activities[48].

Under natural conditions, the elevation of deltaic plains is maintained by sediments distributed by rivers, tides and coastal currents. However, man-made projects such as the polderization of the coastal zone or upstream diversions have resulted in tidal amplification[85] and have altered the sedimentation pattern by preventing sediment from depositing on parts of the floodplains[67,86], resulting in shorter-term shallower deltaic subsidence. These rates of subsidence reported for the coastal zone of Bangladesh typically vary from 3 to 8 mm per year[33,84]. However, in Polder 32 (adjacent to the Sundarbans), for example, a combined relative elevation loss of 1–1.5 m was detected when compared with the adjacent natural Sundarbans, accounting for an effective sea level rise rate of 2–3 cm per year[11,85]. This substantial loss of relative elevation is attributed to the interruption of sedimentation inside the embankments, an amplified tidal range and the removal of forest biomass[11,50,85].

The lowered elevation inside the polders has also resulted in an increased risk to tidal, pluvial and fluvial flooding. In 2009, for instance, Cyclone Aila (a weak, category 1 storm) breached embankments around Polder 32, causing widespread inundation that lasted for up to 2 years until embankments were repaired[11]. However, the reconnected floodplain accreted by approximately 18 cm during this time, equivalent to two decades of normal sedimentation[11]. Such rapid sedimentation highlights the effectiveness of the GBM rivers and tidal distributaries in delivering sediment to subsiding, sediment-starved areas.

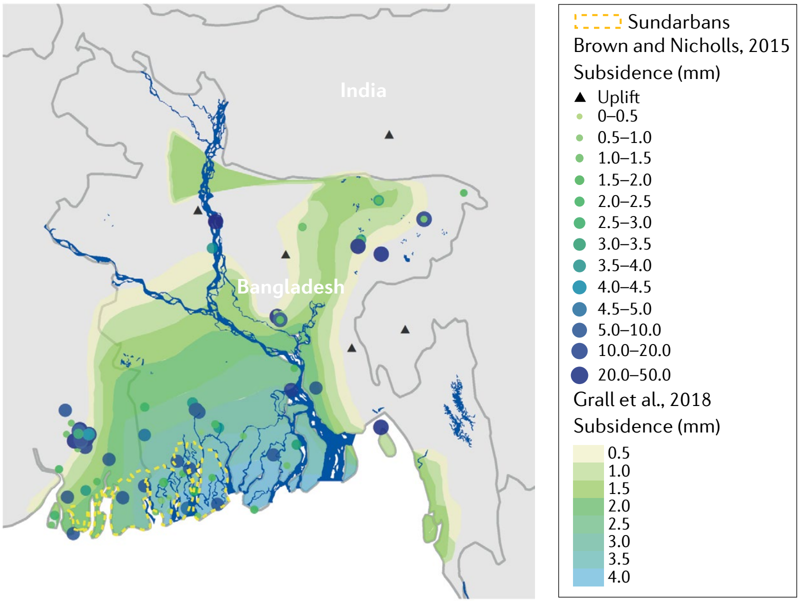


Fig. 5 | **Subsidence across the Ganges–Brahmaputra–Meghna delta.** Averaged Holocene rates that exclude short-term compaction are illustrated as regional zones[39], whereas point measurements include both Holocene rates as well as anthropogenic-induced short-term compaction rates within urban centres[12].

Delta front mobility. With persistent net land gains, the GBM delta is classified as a prograding delta[16,19,87]. However, the rates and dynamics of progradation and erosion vary along the delta front. The most rapid rates of new land development occur in the Meghna river mouth estuary[16,18,88–91], where emergent intertidal bars coalesce over decades into large vegetated islands that could persist for millennia. During this growth phase, the margins of these islands can be heavily modified by channel migration and local bank erosion, but the net pattern is overwhelmingly progradational. Reconstructions of land growth in the Meghna Estuary show that such net progradation has persisted at annual rates of between 7 km^2 (REFS[16,87]) and 20 km^2 (REFS[19,89,92]). The range in observed rates reflects both natural variations and differences in methodology, such as the timescale of observation and the particular area of the delta plain included in the analysis.

West of the active Meghna Estuary, the delta front becomes increasingly sediment-starved with distance from the fluvial sediment source. Erosion of approximately 4.6 km^2 per year has been observed along the Sundarbans coastline between 1972 and 2010 (REF.[93]), with such net erosion patterns and widespread shoreline retreat being well documented for this western region of the delta[92–95]. However, these rates of loss are relatively low, as this region encompasses many thousands of square kilometres of intertidal delta plains, normalizing this land loss to less than 0.01% per year. Furthermore, widespread sedimentation in the upper tidal channels has accounted for approximately 90 km^2 of land accretion in recent decades, offsetting about half of the land loss occurring along the coast[68]. These spatially variable changes along the GBM shoreline are driven not only by natural, autogenic delta processes[16,94,95] but, increasingly, their response to anthropogenic perturbations, such as the Farakka Barrage diversion and widespread polder construction[19,68,85,96]. Despite these general correlations between process and response, a direct link with potential driving mechanisms (such as changes in sediment flux, tidal dynamics or land use change) is currently missing.

Predominant impacts

The changes in geomorphic states result in increased flood risk, reduced navigability in the dry season, loss of land to erosion, increased soil and groundwater salinity, arsenic contamination, habitat and species endangerment and extinction, loss of livelihoods and ecosystem services, people's displacement, changes in crop production, deterioration of water quality and an increase in poverty[56,97,98]. The most prominent impacts resulting from changes in geomorphic states are discussed in this section (FIG. 6).

Direct floodplain land loss or gain. Riverbank erosion is one of the foremost geomorphic processes responsible for pushing new households into poverty in Bangladesh, as it results in the destruction of agricultural land, homes and industries and the displacement of up to 300,000 people each year[99–101]. Approximately 15–20 million people are at risk from the impacts of erosion across Bangladesh[100], and more than 87,000 ha (870 km^2) of land has been lost since 1973 (REFS[78,100,102]) due to the

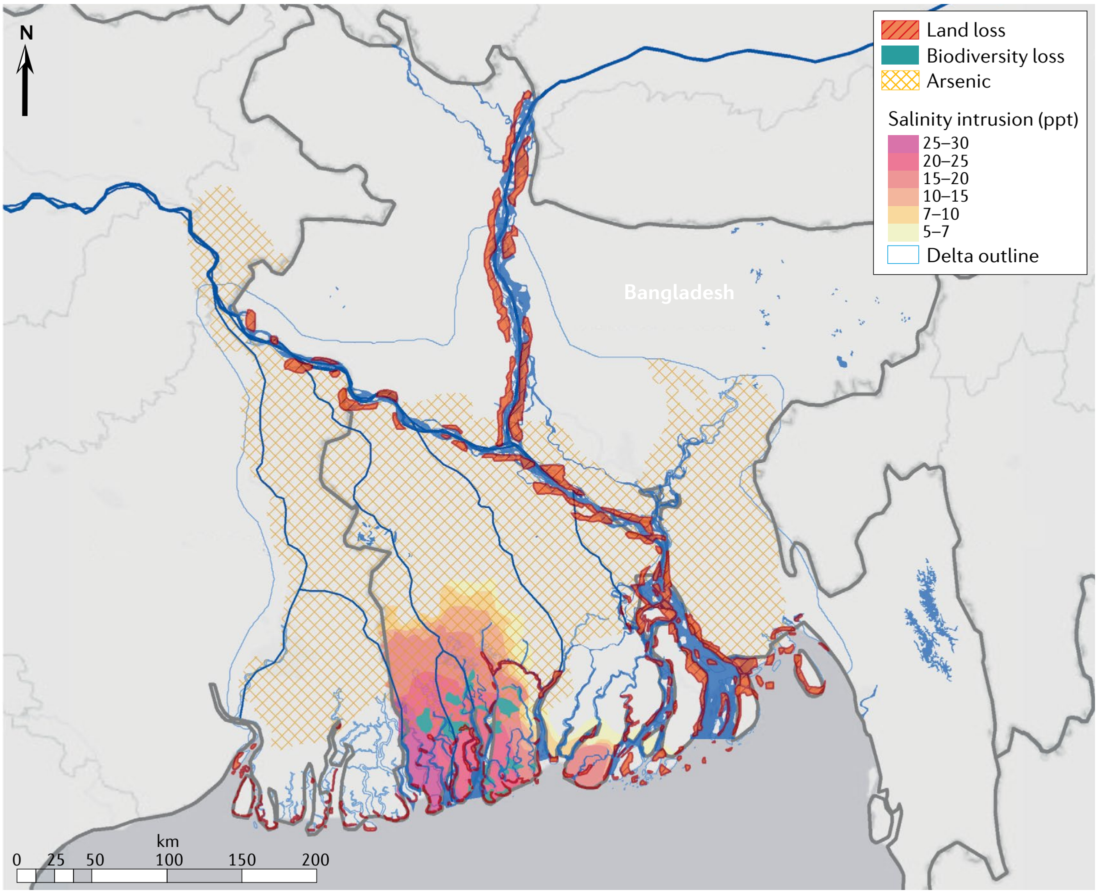


Fig. 6 | **Predominant impacts of geomorphic change in the Ganges–Brahmaputra–Meghna delta.** Map based on 36 studies that spatially assess geomorphic impacts (for full list of references that contributed to this figure, see Table 4 in Supplementary information). Flood risk is not included due to its widespread and sporadic nature. South-west Bangladesh experiences a wide range of environmental impacts caused by geomorphic change, and although land generation is vast in the river mouth (not shown), land loss is prevalent along channel margins and coastal shorelines. Saline intrusion is most widely reported in the south-western region of Bangladesh, which occurs during the dry season. ppt, parts per thousand. Credit: Esri, HERE Technologies, Garmin, (c) OpenStreetMap contributors and the geographic information system (GIS) user community.

Jamuna's westward migration and high rate of widening (FIG. 6). In comparison, only 11,680 ha (117 km^2) of new land was accreted over the same period from 1973 to 2010, occurring only along the left bank. This trend implies that the river consumes 7 ha per year of valuable floodplain land for every hectare it creates[78,102]. In the case of the Ganges, studies disagree on whether the river erodes or accretes more land. Between 1975 and 2015, the total amount of riverbank erosion was roughly 500 km^2 and the total amount of accretion was 833 km^2, implying a greater rate of accretion[103]. However, other studies have found rates of erosion to be higher in the last 100 years[104] and more balanced in the last 40 years[69].

The livelihoods of riverbank and charland dwellers are persistently impacted by the dynamic interplay of erosion and deposition. These communities move with the riverbanks, losing and rebuilding their houses as the rivers repeatedly capture their lands and homes[105]. They tend to relocate to recently accreted floodplain lands that have similarly high flood and erosion risks[106]. In the Jamuna River region, there are more than 100,000 ha of charlands but only 40% of the islands remain stable for more than 6 years, resulting in some charland dwellers having to migrate at least once every 6 years in 60% of the Jamuna[107].

Increased flood risk. Changes in geomorphic states and shifting land use mean that flood risk could decrease in certain areas of the delta but increase in other areas. The shifts in the causes and severity of flood risk have consequences for crop and house damage, income, livelihoods and the spread of water-borne diseases[67,100].

Pluvial (rainfall-induced) flood risk has most notably increased in the poldered area of the coastal zone, particularly in the south-west[11,67,75]. During the monsoon and high tidal levels, the water level in the rivers and channels is higher than land levels within polders, causing extensive drainage congestion of monsoon waters and waterlogging across the poldered landscape[11,67,86,108]. By the 1980s and 1990s, just a decade after constructing the polders, waterlogging covered more than 100,000 ha of land[108]. Polders in the south-western region of Bangladesh alone increased the pluvial flood extent by 334 km^2 (REF. [75]) due to this extensive waterlogging, rendering land unproductive. This phenomenon was observed in Polder 24 (within the Jessore district), where approximately 50% of the land had developed beels and wetland areas on formerly productive paddy land[86]. Subsidence within the polders has also increased the risk to tidal flooding in this region, both from sudden, dramatic cyclonic storm surges and from the gradual rise in mean high water in the region (tidal amplification) caused by the polders themselves[11,85].

Beels
Shallow wetlands where the water level changes seasonally, supporting dry-season agriculture.

Contamination of soil and groundwater. Arsenic contamination of groundwater and soil is the largest geochemical threat to public health in the GBM delta region, with levels reaching more than 100 times the World Health Organization's (WHO) regulations[109,110]. From the outset of this health crisis, the correlation between delta geomorphology and the distribution of arsenic was widely recognized at both regional[111–116] and local[117–121] scales. These correlations reflect the numerous roles that the geomorphic distribution of delta sediments and stratigraphy play in controlling arsenic-impacting variables; for example, the vertical recharge and lateral flow of shallow groundwater[113,118], hyporheic flow exchange along river channel margins[122–124], organic carbon sources[121,125] and protective palaeosol aquitards[114,126–128].

The most commonly understood origin of arsenic in the GBM delta is from the weathering of fluvial sediments eroded from typical crustal rocks in the upper catchments of the Ganges, Brahmaputra and Meghna rivers. Arsenic then becomes bound to iron-oxide coatings that are ubiquitous on GBM delta sediments. As these sediments become buried below the water table, the microbially mediated reduction of iron oxides (for organic respiration) leads to dissolution and the mobilization of arsenic to the surrounding groundwater[110,112,129]. Thus, the transport, deposition and burial of sediments within different geomorphic settings along trunk channels, distributaries and overbank areas leads to stratigraphic units (aquifers) that vary in dimension, architecture, grain size and geochemical composition. Each of these geomorphically controlled factors plays a crucial role in regulating the distribution of arsenic-contaminated groundwater[111,119,122,130].

Indeed, coarser sediments and steeper channel gradients in the braided-river settings of the upper delta serve to enhance groundwater recharge and transport, generally resulting in the Brahmaputra–Jamuna River and the Old Brahmaputra River being less affected by arsenic contamination[113,114,131]. Similarly, remnant geomorphological units, such as the Pleistocene Madhupur and Barind Tracts of northern Bangladesh (FIG. 1), are not affected by arsenic contamination[114,120,127,132]. Rather, arsenic concentrations tend to be highest in the tidally influenced backwater zone of the lower delta of southern Bangladesh, where the lower elevation and less dramatic surface topography reduce recharge rates and aquifers are fine-grained with higher organic content, which all favour the release and build-up of arsenic[110,129,131] (FIG. 6). Here, the distribution of groundwater arsenic is also highly variable at scales of 10–100 m, with patterns closely correlated with the local fluvial geomorphology that controls the sedimentary and stratigraphic character of the aquifer system[112,114,118].

Soil and groundwater salinity is another geomorphology-linked geohazard affecting large populations across the lower GBM delta and deltas globally[133,134]. In Bangladesh, much of the shallow groundwater salinity originates as estuarine water deposited in the late Holocene channel and channel bar sands[135,136]. In the modern delta, decreasing river and sediment discharge through the south-western region has also caused the dry-season salt-water front to progressively move inland[19,56,98] (FIG. 6). The polders aggravate the situation, as they prevent the natural mechanism of flushing away saline water and soils from the floodplain during the monsoon season. In 1992 and 1993, the area impacted by increased salinity was 23,408 ha, resulting in maximum yield losses of approximately 86% for high-yielding variety boro rice, followed by aman rice, which lost a maximum of 71%[137]. These losses have triggered a large number of farmers to forfeit rice farming and change to less nutritious crops, such as chillies[98], or (for a selected few) convert to salt-water shrimp farming. The shift to shrimp farming has subsequently impacted livelihoods and migration patterns[2,67,138]; shrimp farming requires 10% of the labour needed for rice farming[2,139], rendering people jobless and forcing migration to find an alternative source of income.

Loss in biodiversity. The increase in saline intrusion in the south-western delta is one of the leading drivers of biodiversity loss in the globally important Sundarban mangrove forest[57,140,141]. The extent of the Sundarbans, home to 373 faunal and 324 floral species[141], has remained stable[142]; however, up to 25% of the forested area has experienced an overall negative trend in biodiversity[63,142] (FIG. 6). Part of this trend is likely due to the dieback of the more freshwater-reliant *Heritiera fomes*[63,94,142,143], the predominant and oldest mangrove tree species that is struggling to survive in more saline environments. Average minimum monthly freshwater discharge rates exceeding $194.4\,\mathrm{m^3\,s^{-1}}$ are required to mitigate this dieback, whereas the area is currently receiving between near zero and $170\,\mathrm{m^3\,s^{-1}}$ during the dry season as a result of human interferences within the Ganges Basin[63]. As a consequence of such impacts, the Sundarbans have been classified as endangered under the International Union for the Conservation of Nature (IUCN) Red List of Ecosystems[144].

Dams and diversions have also increased siltation, damaging migratory routes as well as spawning grounds for fish[145]. The Farakka Barrage has, for instance, negatively impacted the breeding and raising grounds for 109 species of Gangetic fish and aquatic plant species, having implications for the wider ecosystem[57]. Along the Old Brahmaputra River, siltation, environmental degradation and human encroachment have similarly caused declines in fish catches and severe declines in Ganges river dolphin populations[146].

Societal responses

Societal responses to the geomorphic impacts differ across scales, from individual to country-level responses. On an individual and local scale, communities have adopted practices of sharecropping and shared ownership of livestock. This approach requires less upfront investment and diversifies livelihoods, making inhabitants of highly vulnerable lands more resilient to environmental stresses[105]. Local communities have often also led the way in adapting to ever-changing environments. For instance, before the mega-infrastructure project of polderizing the coastal zone of Bangladesh, local communities used to build small-scale temporary earthen embankments that would protect lands from saline water intrusion, but allow monsoonal freshwaters to deposit nutrient-rich sediments onto floodplains that simultaneously raised the land[67,147]. In 1990, a civil movement was formed to adopt the traditional method in the whole region of Khulna-Jessore, and embankments were locally breached to relieve waterlogging inside the polder[147]. In the late 1990s, after an extended period of dispute, the Government of Bangladesh recognized this effective solution to the drainage congestion problem, and officially named this management response Tidal River Management (TRM)[67,148–150]. Another community-level measure in the current poldered environment has been to locally excavate silted-up channels and transport this sediment into the polders to enable the growth of crops, particularly vegetables[138]. Population resettlement and/or migration as a result of geomorphic impacts also takes place, but is typically the 'last resort', despite the gravity of the risks that are often faced[151].

On the national decision-making scale, the responses are very different. Bangladesh spends millions of dollars every year to try to stabilize its riverbanks, across approximately 6,000 km of navigable waterways[152]. Engineered structures such as embankments, groynes, cross-dams and sluice gates have dominated sediment and flood management practices in Bangladesh for decades[153]. Currently, the Bangladesh Water Development Board (the government agency responsible for water management) operates and maintains 9,950 km of embankments, 5,111 km of drainage canals and 13,950 flood-regulating structures[153]. This focus is closely interconnected with the ongoing policy attention on land reclamation and accelerating the creation of new land: offshore cross-dams were constructed in the 1950s, the Land Reclamation Project was implemented in the 1970s, Meghna Estuary studies were undertaken in the 1990s, the National Water Management Plan was established in the 2000s and the BDP2100 was realized in the 2010s.

Over the last decades, the coastal region of Bangladesh has seen many development projects related to water management that have played fundamental roles in modifying land use patterns and morphological processes[138]. Some examples include the donor-financed CEP (1968 onwards), which saw the polderization of the coastal zone; the Gorai River Restoration Project (1998–2007), which aimed to excavate the Gorai River channel to increase dry-season flows and restore fish populations; and the Coastal Zone Development Programme, Coastal Embankment Rehabilitation Project (1996–2002) and the Khulna-Jessore Drainage Improvement Project (1994–2002), which have all attempted to alleviate the drainage congestion problem caused by the first CEP, which continues to be a challenge today[138].

Numerous management measures have been suggested to address current and future geomorphic challenges, ranging from large-scale engineering works to local farm-scale resilience measures, in line with the BDP2100 (TABLE 1). The BDP2100 focuses on 'no-regret' measures that are desirable, cost-effective and flexible in light of uncertain future climate and socio-economic scenarios[29]. As evident, a trade-off must inevitably be made between the displacement of people and livelihoods from deltaic plains and achieving maximum sediment deposition to build elevation and reduce salinity intrusion[154–157]. Effective management will require a mosaic of complementary measures and the collaborative involvement of stakeholders[158] including decision-makers, researchers, engineers, local authorities and local communities.

Knowledge gaps

There is growing pressure on deltaic communities due to increasing threats from climate change and population growth, making the sustainable management of these systems critical. However, crucial knowledge gaps remain.

Multiscale perspective of geomorphic change. The geomorphic behaviour of many large deltas observed today is a combination of responses to drivers and pressures on a range of timescales, including sudden shocks and longer-term gradual changes. Disentangling process–response mechanisms remains a challenge[9] (FIG. 7). For instance, neotectonic activities such as uplift, tilting or subsidence occur gradually over a long period of time, whereas seismic events (like earthquakes) take place over a short period of time, but can generate morphological responses for years or decades after the event[17,36,159]. Human perturbations to the system tend to result in rapid adjustments, but the precise nature of the response depends on the boundaries of the system and the scale of disturbance[36]. Attempting to map the scales of change reported in the literature (FIG. 7a) could be the first step to getting a clearer and more complete understanding of the multilevel dynamics observed.

For the GBM delta, most geomorphic understanding is focused on the present and the past 60 years (FIG. 7a). Channel avulsions, fluvial sediment distribution and coastal stability during the Holocene are also regularly investigated. However, there is a lack of scientific attention on the two most fundamental temporal scales required for underpinning policy decisions: the decadal to centennial scale of processes, and how these might behave in the future[9,41]. As most management infrastructure implemented in the past, and proposed for the future, has a lifetime in the order of 100 years, the lack of understanding at these two scales is concerning. Without knowing how the delta could behave in the future, the ability to plan appropriate management measures is severely limited.

Complexity of interactions. The DPSIR framework is useful in gaining a holistic understanding of environmental and social change, but its structure inevitably simplifies the complexity of the interactions in the

Table 1 | **Compilation of key adaptation measures included in planning documents and their assessment against the goals and criteria defined by the BDP2100**

Adaptation Measure (BDP2100 Goal)	**Aim of Measure**	**Assessment criteria**				**Wider impacts**
		Cost	**Flexibility**	**Technical feasibility**	**Social acceptability**	
Ganges/Padma Barrage[29] (2)	Construction of new barrage to increase upstream river flow and control salinity intrusion	🟧	🟧	🟧	🟩	+ Improved navigability and surface water availability - Population displacement, disturbance of aquatic ecology, change in natural sediment dynamics
Diversion of water down Gorai-Madhumati River[19,29] (2)	Push the salt-water front further towards the sea and reduce channel siltation	🟨	🟧	🟧	🟢	+ Improved navigability, surface water availability, aquatic diversity, delivery of nurients - Tidal channel reorganisation
Construction of 11 cross-dams in Meghna estuary[29] (1)	Encourage and accelerate land reclamation in the estuary	🟧	🟨	🟢	🟢	+ Socio-economic growth, coastal storm and sea-level rise protection - Change in natural sediment dynamics (tidal distribution), creates more vulnerable land
Mangrove afforestation[29] (3)	To provide storm protection and coastal stabilisation north of Sundarbans and Meghna Estuary	🟢	🟩	🟢	🟩	+ Improved biodiversity, carbon sequestration, eco-tourism - Displacement of populations, less land available for agriculture
Construct new and/or raise existing embankments[29] (1)	Improve flood and erosion protection in economic priority zones	🟧	🟨	🟨	🟩	+ Socio-economic growth, enhanced land productivity - Channel reorganisation, disconnecting floodplain, long-term sediment starvation
TRM in non-saline polders[29,148–150,158,183,184] (4)	Alleviate subsidence-induced waterlogging and channel siltation	🟨	🟢	🟨	🟨	+ Nutrients to floodplains, flush salinity and toxins, improved navigability - Displacement of populations, extended periods of unproductive land
De-polderise[29] (4)	Remove coastal polders to allow natural sedimentation across deltaic plains	🟨	🟧	🟧	🟧	+ Natural regeneration - Social disorder, displacement of populations, extended period of unproductive land
Regular smart dredging in major rivers[19,29,51,155] (6)	Relieve siltation, improve channel capacity and clear submerged chars	🟨	🟩	🟩	🟩	+ Improved navigability, reduces flood risk - Potential biodiversity loss, channel reorganisation
Use sediments from river bed, elevate land[19,29] (1)	Reduce channel siltation and raise lands in south-west Bangladesh	🟢	🟩	🟩	🟩	+ Socio-economic growth, improved navigability - Potential channel reorganisation
Floodplain and erosion hazard zoning[29,156] (1)	Allow space for the rivers to flood and erode river banks in risk hotspots	🟧	🟨	🟧	🟨	+ Natural regeneration, groundwater recharge, flush pollutants - Displacement of populations, loss of livelihoods
Embanking charlands within Brahmaputra[29] (1)	Embank charlands to increase habitable land	🟨	🟨	🟨	🟢	+ Flood protection, economic growth, productive land - Altering sedimentation patterns, creates more vulnerable land
Reintroduce *Bandals*[157] (1)	Stabilise channels and manage riverbank erosion in smaller channels	🟩	🟩	🟩	🟩	+ Flood protection, socio-economic growth - Altering sedimentation patterns
Salt-resistant crop farming in saline polders[29] (6)	Adapt crop farming to ameliorate food security north of Sundarbans	🟩	🟩	🟩	🟢	+ Socio-economic growth, productive land - Potential for pollution from agrochemicals, loss of local crops

Table 1 (cont.) | **Compilation of key adaptation measures included in planning documents and their assessment against the goals and criteria defined by the BDP2100**

Adaptation Measure (BDP2100 Goal)	Aim of Measure	Assessment criteria				Wider impacts
		Cost	Flexibility	Technical feasibility	Social acceptability	
Farmers to leave stems during crop harvest[155] (1)	Crop stems trap sediment and prevent soil erosion along river and channel banks	🟩	🟩	🟩	🟩	+ Reduced sowing requirements - Less productive land use
Out migration[29] (1)	Move people away from high vulnerability zones	🟧	🟧	🟧	🟧	+ Natural regeneration - Social disorder, displacement of populations, loss of livelihoods

The colour of each cell represents the performance of the measure against each assessment criterion, with green being positive (inexpensive, flexible, feasible and acceptable) and orange being negative (expensive, inflexible, unfeasible and unacceptable). The BDP2100 goals in the first column are: (1) Ensure safety from floods and climate change-related disasters; (2) Enhance water security and efficiency of water usages; (3) Ensure sustainable and integrated river systems and estuaries management; (4) Conserve and preserve wetlands and ecosystems and promote their wise us; and (6) Achieve optimal and integrated use of land and water resources. This table does not incorporate all possible measures.

system. Changes in geomorphic states are not only caused by the defined drivers and pressures but also through feedback with other geomorphic states. For instance, channel migration will influence the location of sediment reaching the delta, shaping the progradation of the delta front, as well as playing a role in determining which areas are more likely to subside or aggrade[18]. Similarly, patterns of subsidence will also play a role in shaping the ways in which channels migrate[34,160].

Despite acknowledging the interdependencies of geomorphic processes, 86% of the 427 studies included in this Review only assess a maximum of two geomorphic states, with 60% assessing only one. This limitation can cause a fragmented understanding of dynamics, with the potential to focus on only part of the system. Promisingly, there is no suggestion here that major interactions are entirely overlooked from the studies based on more than one state, but just 40% of the geomorphic literature base is represented (FIG. 7b). As emerging geomorphic problems, particularly in the poldered region, have been attributed to the absence of a holistic understanding of hydromorphological characteristics[67,108], it is crucial that response measures use system-wide approaches[2,26]. There is therefore a growing urgency for more integrated, interdisciplinary and transdisciplinary studies that combine hydrological, morphological, social and political dynamics across the entirety of the GBM delta, particularly with local stakeholders, alongside continued disciplinary research.

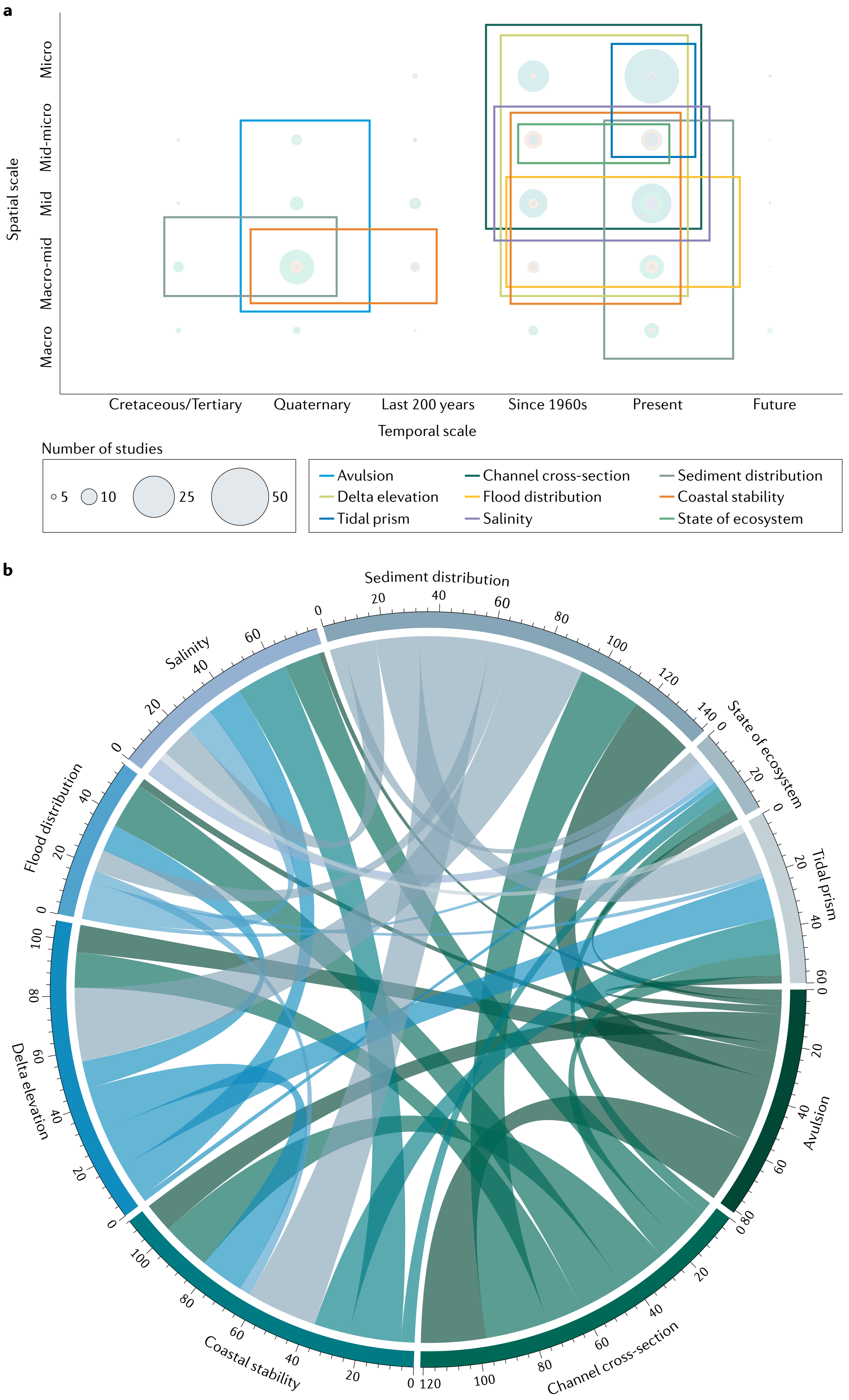
Human–nature system. The GBM delta is very much a human–nature system[24], yet the scientific focus of human–geomorphic interactions is centred around two predominant events in time: the polderization of the coastal zone in the 1960s–1980s, and the construction of the Farakka Barrage in 1975. The anthropogenic changes in the environment associated with these two events have been assessed as exogenous alterations to the natural system. A spatially explicit understanding of how such development projects, urbanization and changing agricultural and aquaculture practices have affected geomorphology and, similarly, how the natural geomorphic landscape has shaped populations is still emerging.

Anthropogenic activities are being integrated within conceptual environmental models[65,161–163] in the sustainability sciences (coupled human and natural systems (CHANS)[164]) and, more recently, in the hydrological sciences (socio-hydrology[165]). Interactive interfaces (such as for agent-based models) enable the different components of the system to be linked, as undertaken in the Deltares 'Bangladesh Metamodel' (informing the BDP2100 (REF.[166])) or the ESPA Deltas project in coastal Bangladesh, which links a suite of models from the social and biophysical components of the system[2]. These models represent the first steps in bringing the key components of the system together. However, they still do not incorporate the multiscale representation of geomorphological delta-building processes under increasing pressures. In the absence of this fundamental biophysical understanding, these coupled system representations will omit some of the most important dynamics of the system.

Future behaviour of the delta. Although there is widespread evidence of delta evolution, there are very few projections of the future geomorphic behaviour of the delta. Only 5% of the 427 studies reviewed here look at how the delta could behave in the future (FIG. 7a; see Supplementary information). There are no studies examining the future of land loss as a result of channel or coastal front migration within the GBM delta. Such

Fig. 7 | **Key systemic gaps in scientific understanding of geomorphic change in the Ganges–Brahmaputra–Meghna delta.** Diagrams based on a review of 427 studies. **a** | Processes occurring on a range of spatial and temporal scales. Circles show the number of studies that assess each spatio-temporal scale, with colours representing the different geomorphic processes. Squares highlight the predominant spatio-temporal focus of each process. Spatial scale categories are classified as macro (catchment-wide or wider), macro-mid (Bay of Bengal and/or delta-wide), mid (river or coastal zone), mid-micro (division level) and micro (sub-division level). **b** | Chord diagram of topical combinations of studies that assess two or more geomorphic processes in the Ganges–Brahmaputra–Meghna (GBM) delta. Width of chords indicates the number of studies.

▶


a
Spatial scale
Micro
Mid-micro
Mid
Macro-mid
Macro
Cretaceous/Tertiary
Quaternary
Last 200 years
Since 1960s
Present
Future
Temporal scale
Number of studies
5
10
25
50
Avulsion
Delta elevation
Tidal prism
Channel cross-section
Flood distribution
Salinity
Sediment distribution
Coastal stability
State of ecosystem
b
Sediment distribution
0 20 40 60 80 100 120 140
State of ecosystem
0 20
Tidal prism
0 20 40 60
Avulsion
0 20 40 60 80
Channel cross-section
0 20 40 60 80 100 120
Coastal stability
0 20 40 60 80 100
Delta elevation
0 20 40 60 80 100
Flood distribution
0 20 40
Salinity
0 20 40 60

estimations could provide fundamental tools to guide erosion and sediment management strategies and policies, as desired by the BDP2100 (REF.[29]), with the explicit acknowledgement of the inherent uncertainties and limitations[102,167].

The few studies that do look at future behaviour of the delta predominantly focus on the future trends in fluvial sediment delivery to the delta in the face of climate change and increased upstream sediment trapping. Although climate change is expected to increase monsoonal rainfall and sediment flux over the twenty-first century, the signal is much smaller than the direct anthropogenic interference[74]. Sediment flux to the delta could be reduced by as much as 88% by the end of the century (reducing from 669 MT per year in a 'pristine' world to 79–92 MT per year by the end of the century), considering a range of possible socio-economic scenarios and assuming all 414 planned dams within the GBM delta catchment will be constructed (285 in Nepal, 108 in India, 12 in Bhutan, 8 in China and 1 in Bangladesh)[5,74]. The potential expansion of the western route of China's South-to-North Water Diversion project, which would see the diversion of 200 billion m^3 from the Yarlung Tsangpo (upstream Brahmaputra) to the Yellow River[168], and India's National River Linking Project (NRLP), which aims to connect 44 rivers via 9,600 km of canals[169], could dramatically alter the sediment delivery to downstream Bangladesh. Water diversions associated with India's NRLP could further reduce the Ganges sediment load by 39–75% before entering Bangladesh, whereas Brahmaputra diversions could lead to a 9–25% reduction in suspended sediment load[169]. Such drastic reductions in sediment delivery, if manifested, would certainly alter rates of land accretion and the morphological balance of the delta with sea level rise and subsidence[4,74,169].

Although climate change and sea level rise remain major concerns for Bangladesh in the coming decades, the sustainability of the GBM delta is expected to be influenced much more by the direct control of local and regional engineering and management programmes[68] and decisions taken upstream[102]. Projections of future geomorphic processes are therefore urgently required, particularly focusing on how these geomorphic dynamics respond to the growing socio-economic challenges and regional management programmes (TABLE 1), as well as to increasing management plans in upstream nations.

Summary and future directions

The importance of weaving geomorphology across science, engineering, policy and society is critical for recognizing deltas as evolving socio-hydromorphological environments. Geomorphology can drive vulnerability or sustainability in large dynamic deltas such as the GBM delta, as it continuously defines the ever-changing deltaic landscape. To achieve long-term climate resilience in the world's large delta systems, management and policy decisions need to mainstream geomorphology into assessments of deltaic risk, rather than implement reactive short-term responses to existing impacts. This imperative is echoed in the BDP2100, which aims to better prepare the GBM delta for the uncertainties of climate change. However, these goals cannot be achieved without increased collection of empirical data and monitoring of ongoing processes; improved theory of delta dynamics; the development of an array of models, ranging in complexity from simple stylized models to complex numerical models; and the development of tools and evidence to inform critical policy decisions and priorities.

The GBM delta is exceptionally data scarce, despite being at particularly high risk from climate change, extreme hazards and anthropogenic alterations within and outside its national borders. More and improved monitoring and data collection are needed across the catchment[29], including more regular and widespread water and sediment discharge measurements, and improved data sharing between China, Bhutan, Nepal, India and Bangladesh to enable the whole transboundary system to be better understood as one entity. Alongside field data collection, continuing advancements in alternative data collection and processing offer exciting opportunities, including satellite data to monitor the extent of freshwater bodies (for example, Global Surface Water Explorer[170]), high-resolution night light data for estimating flood damage[171] or the use of mobile-based technologies to map population movements after flood events[172], map poverty[173] and obtain rainfall[174] and groundwater-level[175] data.

The lack of data from the GBM delta has also limited our theories and conceptualizations of the current and potential future dynamics of the delta[1,176]. A growing body of research takes an integrative view of the whole delta system, building on the foundation of targeted research conducted over the last few decades. Continued development and testing of theories that integrate the delta's changes at multiple scales is necessary to generate the scientific understanding needed for predicting future changes and underpinning the aims of the BDP2100.

Improved theoretical understanding of the delta should be translated into modelling tools. There have been some impressive advances in hydrodynamic modelling of the delta[177] that quantify tidal and fluvial flows throughout the system and estimate sediment transport. However, morphological predictions obtained from hydrodynamic models are not dependable in the medium and long term, especially for cohesive sediment systems[178]. Thus, whereas these detailed models provide useful tools, they cannot be expected to be a panacea for the challenges of predicting deltaic change. One possible avenue would be the development of intermediate complexity models, based on geomorphological theory, such as the CAESAR-Lisflood[179] and ASMITA[180] models. However, these models do not yet incorporate all of the main drivers and processes that are central to the GBM delta, so further model development is required[181,182].

There is currently still a fundamental gap between the scientific research produced and the information required for decision-makers and policy-makers. The BDP2100 outlines key research requirements for new knowledge (Table 14.4 in the BDP2100 strategy[29]), including an understanding of how different management options affect tipping points, and how to strike the right balance between mitigation and adaptation measures. These areas remain opportunities for future efforts by scientists researching the GBM delta and could be especially useful for the development of further policy plans such as the BDP2100. As evident, deltas are dynamic geophysical features that do not adhere to political boundaries. Their long-term sustainability therefore depends upon open data-driven water, sediment and land use dialogues amongst all governing bodies and stakeholders.

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Author contributions

A.P. conceptualized the research, analysed the literature and wrote the manuscript. S.G., E.B., M.S.A.K. and J.W.H contributed to the discussion and reviewed the manuscript prior to submission. Conceptualization and development of the manuscript were supervised by E.B. and J.W.H.

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