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Supplementary information

Geomorphic change in the Ganges–Brahmaputra–Meghna delta

In the format provided by the authors and unedited

Supplementary Information

Methodology

A systematic literature review was undertaken to identify and characterise peer-reviewed studies assessing geomorphological dynamics in the GBM delta. Only literature in the Web of Science (WoS) (Thompson Reuters) and SCOPUS (Elsevier B.V.) databases were included, where key word searches were performed to extract all relevant articles published before September 2020. The search queries used for the study included *Ganges OR Brahmaputra OR Meghna OR Jamuna OR Ganga OR Padma,* limiting studies to the delta by using *AND Bangladesh OR Bengal OR Delta,* and extracting relevant morphological studies by using *AND *morph* OR subsi* OR *sediment* OR erosion* OR salin* OR avuls* OR tid* OR ecosystem OR biodivers* OR flood* OR *channel**, where the Asterix symbol represents any word beginnings or endings. Only the title, abstract and keywords were searched, and no limit was set to year of publication. This search returned a total of 2,942 articles, ranging from 1863 to 2020.

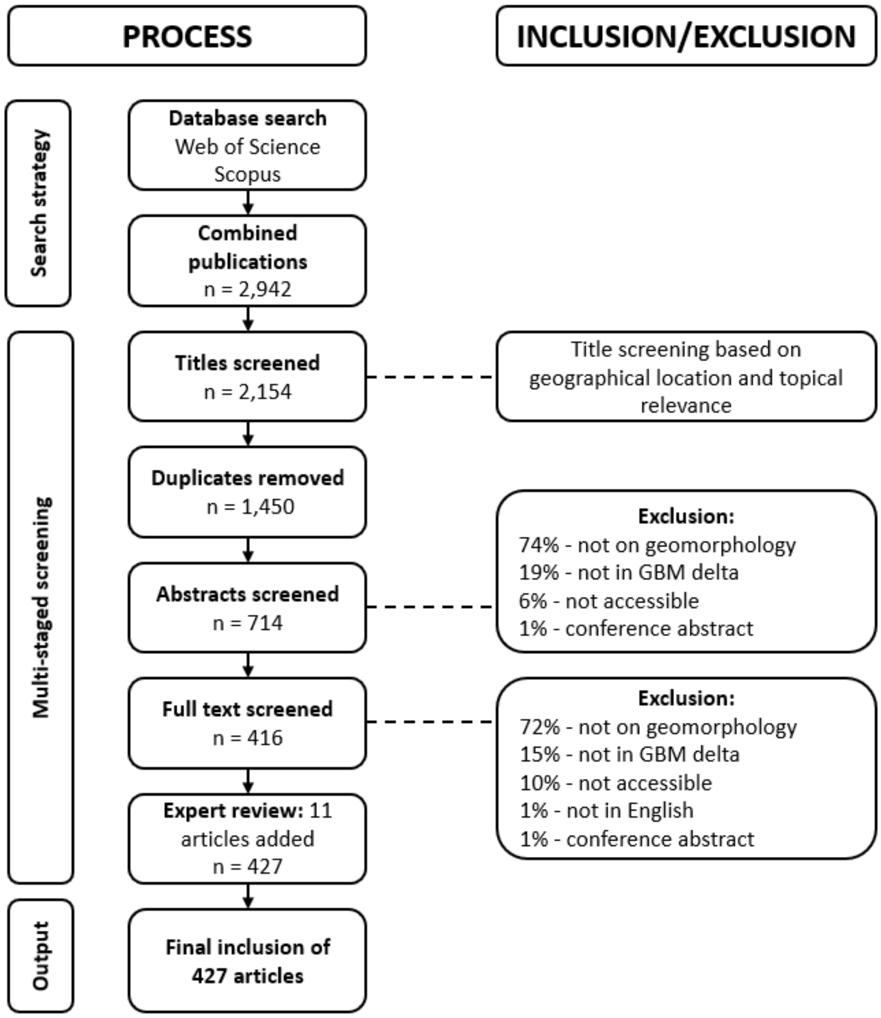

Figure 1: Structure of systematic literature review process

The screening process was done in multiple stages, as shown in Figure 1. The initial screening removed unrelated articles, assessed by their titles, and duplicates. This reduced the total number of articles to 1,450 for abstract review. Articles that met any of the following exclusion criteria during abstract screening were removed from further analysis: (1) language other than English; (2) not related to morphology in the GBM delta; (3) related to morphology but not in the GBM delta; and (4) articles that were inaccessible (majority of which were book chapters). A total of 736 articles were removed during the abstract screening process, predominantly due to criteria 2 and 3 (93% of articles removed). Following this screening process, the full text of 714 publications was reviewed, during which, a further 298 articles were excluded. These articles were also predominantly excluded due to criteria 2 and 3. A final database of 416 articles were then assessed in detail and classified.

To verify that the initial search results were representative of the geomorphic literature for the GBM, one of our paper's co-authors not involved in the first-round search conducted an internal review that led to the addition of 11 articles to the database. The final 427 articles reviewed in this study are published in 210 different journals across the natural, engineering, political and social sciences, illustrating a diverse research interest in the different components of the geomorphic evolution of the GBM delta. The full list of articles is available as the Supplementary database.

Applying the DPSIR Framework

As this delta system is complex and interacting with a large human population that both benefits from and impacts the environment, there is a need to understand how natural and anthropogenic activities shape the environment at a range of spatial and temporal scales[1–3]. The DPSIR framework has been widely acknowledged as a framework for linking human activities with environmental challenges, and bridging scientific disciplines with relevant policy and management[1–3]. Moreover, it has been recognised as a tool to organise and structure scientific information[1,4] and deal with a range of generic and site-specific problems, particularly in coastal, estuarine and marine systems[2]. The framework is made up of a chain of causal links, starting with 'driving forces' through 'pressures' to 'states' and 'impacts' on environments, livelihoods and functions, which lead to 'responses'[5]. In essence, this conceptual model acts as an organisational framework, enabling a logical and hierarchical synthesis of information, and simplifies complex cause-effect relationships between natural hazards, human activities, and the environment[2].

The DPSIR framework was therefore applied to organise the literature and identify the aspects of geomorphic change and dynamic interactions assessed in each paper. For the purpose of this review, the 'drivers' are defined as natural forces that shape the delta, 'pressures' are defined as the human activities that affect geomorphic processes, the 'state' of the deltaic environment is defined as a change in geomorphic states in response to drivers and pressures, which in turn may have environmental or socio-economic 'impacts'. The 'responses' by society or policy makers are reactions to these impacts[5], and in this study take the shape of environmental management schemes or human adaptations that can consequently continue to affect the environment through feedback loops.

As this framework has not yet been applied to geomorphic processes in deltaic environments, the indicators for each of the DPSIR categories were defined by the authors (see Table 1), based on expertise in hydrology, geomorphology, policy and engineering. Alongside this classification of the literature, the review also extracted the spatial and temporal scales, methodological approaches, and key conclusions from each study.

Table 1: Geomorphic indicators defined for the DPSIR framework

Natural Drivers	Human Pressures	System States	Impacts	Responses
Sea level rise*	Land use change	Channel avulsion/lobe switching	Changes in flood dynamics	Embankments and polders
Tides	Hard structures	Channel cross-section and bankline stability	Channel siltation	Building elevation (e.g., Tidal River Management)
Cyclones	Flow modification	Sediment distribution	Land loss/gain	Drainage and irrigation management
Waves	Altered sediment budget**	Delta elevation	Loss/gain in biodiversity	Erosion control
Tectonics	Transportation infrastructure***	Flood distribution	Arsenic distribution	Dredging/channel modifications
Subsidence*		Coastal front stability	Change in agricultural production	Ecosystem restoration
Underlying geology		Tidal prism	Damage and disruption to physical assets	Land use change
River discharge		Salinity	Impacts on health and wellbeing of population	Migration/re-settlement
Monsoon		Ecosystem state	Economic gain/loss	Disaster management****

** These natural drivers also have anthropogenic influence*

*** Altered sediment budget includes dredging/redistributing and trapping*

**** This includes bridges, roads and navigation infrastructure*

***** This involves immediate response: cyclone shelters, incentives, warning systems*

Statistical Findings

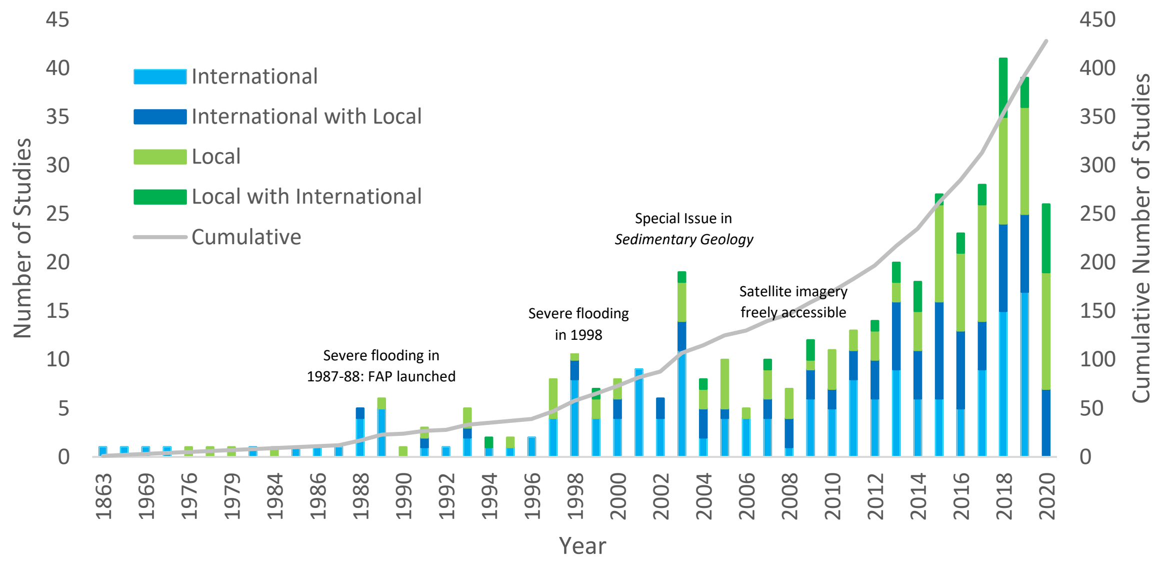

Figure 2: Temporal trend and origin of geomorphic studies published for the GBM delta. *The majority of publications on GBM geomorphology (65%) are led by international authors, here defined as authors affiliated with institutions outside of Bangladesh and India.*

Table 2: Contributing countries to geomorphic literature in the GBM delta. *Bangladesh contributes the greatest authorship to geomorphic science in the GBM delta, involving 152 publications. Local contributions are also likely to be underestimated in our analysis, as it does not distinguish articles by Bangladeshi or Indian authors affiliated to international institutions and does not include articles that are not indexed in WoS or Scopus or written in languages other than English.*

Country of Affiliation	***First Author***	***Contributing Authors***	***Total Contributions***
Bangladesh	63	89	**152**
USA	93	29	**122**
India	87	16	**103**
UK	48	18	**66**
Germany	25	16	**41**
The Netherlands	16	12	**28**
Japan	21	6	**27**
France	15	10	**25**
Australia	12	10	**22**
China	10	7	**17**
Canada	13	1	**14**
Italy	6	4	**10**
Sweden	2	6	**8**
Switzerland	0	6	**6**
Denmark	1	3	**4**
New Zealand	3	1	**4**
Russia	4	0	**4**

Thailand	1	2	**3**
Belgium	0	3	**3**
Singapore	0	2	**2**
Brunei	2	0	**2**
Spain	1	1	**2**
Sri Lanka	1	0	**1**
Norway	1	0	**1**
Papua New Guinea	1	0	**1**
Malaysia	1	0	**1**
Korea	0	1	**1**
Ghana	0	1	**1**
Pakistan	0	1	**1**
Czech Republic	0	1	**1**
Estonia	0	1	**1**
Taiwan	0	1	**1**
Nepal	0	1	**1**
Brazil	0	1	**1**

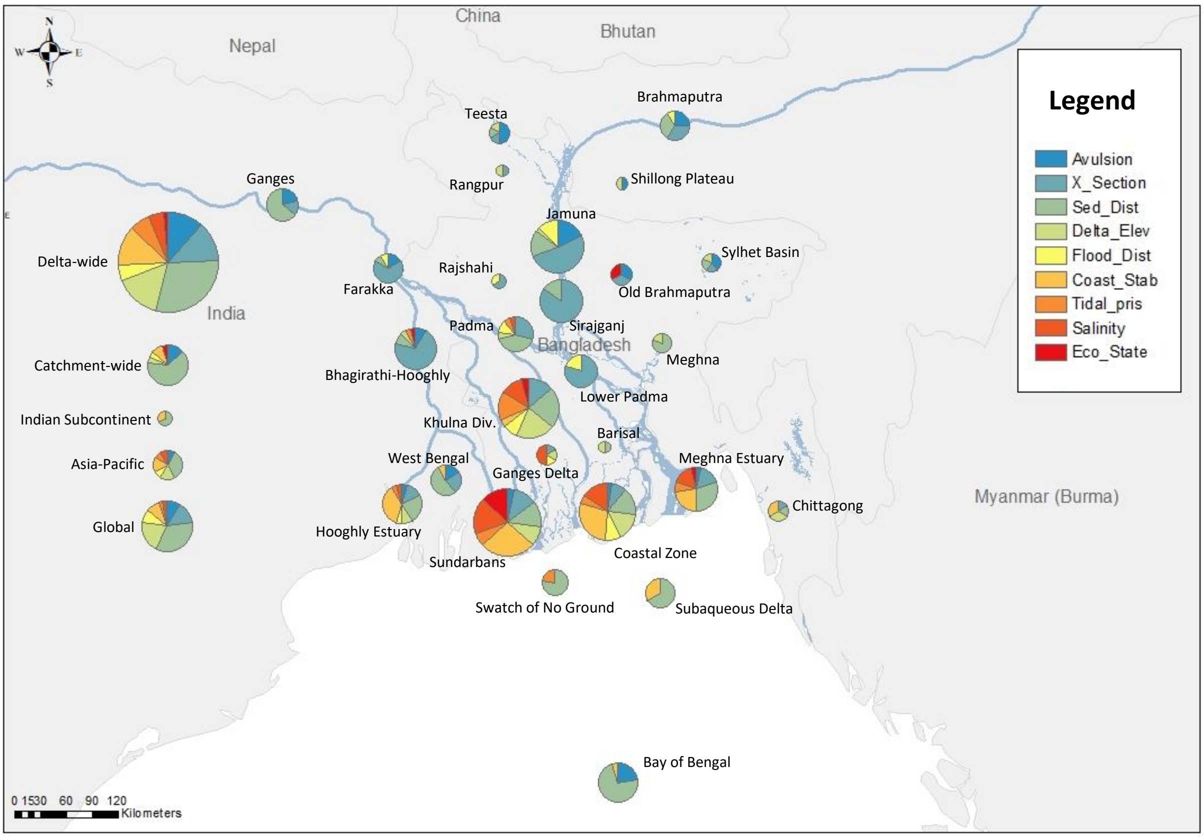

Figure 3: Spatial focus of studies assessing different aspects of geomorphological change*. Large-scale dynamics across the whole delta are the most frequently studied spatial extent. This is likely to be due to the high number of international studies, that tend to focus on larger-scale understanding of delta dynamics, whilst the local studies often focus on site-specific areas where impacts of geomorphic change are more apparent and relevant to local livelihoods.*

Sediment budget estimations

Table 3: Studies assessing fluvial sediment budgets for the GBM Delta, updated from Rahman et al., 2018. *Note the sediment contribution from the Meghna River is negligible in comparison to the Ganges and Brahmaputra Rivers and has therefore been excluded from the table.*

River Basin	Sediment Flux (MT/yr)	Study	Duration	Location	Methodology Used
Ganges	1600	Holeman, 1968	1874 - 1879	Hardinge Point	Unknown
	520	BWDB, 1972 (in Islam et al., 1999)	1966 – 1969	Hardinge Point	Sediment sample data
	375	NEDECO, 1967 (in Islam et al., 1999)	1960	Bangladesh	Unknown
	478.9	Coleman, 1969	1958 – 1962	Hardinge Point	Field measurement
	390	Lupker et al., 2011	2004 - 2010	Unknown	ADCP with sediment depth profile sampling
	680	Milliman and Meade, 1983	Unknown	Hardinge Point	Sediment rating curve
	350 - 600	Hossain, 1992, in FAP24	1980 – 1986	Hardinge Point	Sediment rating curve
	316	Islam et al., 1999	1979 – 1995	Hardinge Point	Sediment rating curve
	502	Barua et al., 1994	Unknown	Unknown	Unknown
	550	CEGIS, 2010	Unknown	Unknown	Unknown
	430 – 729	Thakkar, 2006	Unknown	Unknown	Unknown
	262	Rice, 2010	2006	Hardinge Point	Field measurement
	548	FAP24, 1996	1966 – 1970	Hardinge Point	Sediment rating curve
	200	China-Bangladesh Joint Expert Team – CBJET, 1991	1965 – 1988	Hardinge Point	Unknown
	340	French Engineering Consortium, 1989	Unknown	Hardinge Point	Sediment rating curve
	210	Master Plan Organisation, 1987	Unknown	Hardinge Point	Sediment rating curve
	487	Islam and Jaman, 2006	1976 - 1989	Hardinge Point	BWDB measurements
	401	Abbas and Subramanian, 1984	1981	Farakka	Field measurement
	150 – 590	Rahman et al., 2018	1960 - 2008	Hardinge Point	BWDB measurements
Brahmaputra	800	Holeman, 1968	1874 – 1879	Bengal Delta	Unknown
	1157	Milliman and Meade, 1983	Unknown	Bahadurabad	Sediment rating curve
	607.7	Coleman, 1969	1958 – 1962	Bahadurabad	Field measurement
	541	BWDB, 1972 (in Islam et al., 1999)	1967 – 1969	Bahadurabad	Sediment sample data
	750	NEDECO, 1967 (in Islam et al., 1999)	1960	Bangladesh	Unknown
	541	Kabir and Ahmed, 1996	1993	Bahadurabad	Field measurement
	721	Islam et al., 1999	1989 – 1994	Bahadurabad	Sediment rating curve
	650	Hossain, 1992	1982 – 1988	Bahadurabad	Sediment rating curve
	390	Master Plan Organisation, 1987	Unknown	Bahadurabad	Sediment rating curve
	500	CBJET, 1991	1965 – 1988	Bahadurabad	Unknown
	1028	Barua et al., 1994	Unknown	Unknown	Unknown
	590	CEGIS, 2010	Unknown	Unknown	Unknown
	430	French Engineering Consortium, 1989	Unknown	Bahadurabad	Sediment rating curve
	387	Rice, 2010	2006	Sirajganj	Field measurement
	402	Goswami, 1985	1955 – 1979	Pandu, Assam	Sediment rating curve
	710	Subramanian, 1987	Unknown	Unknown	Unknown
	315- 615	Rahman et al., 2018	1960 – 2008	Bahadurabad	BWDB measurements
Combined	1140 (±200)	Mouyen et al., 2018	2002 – 2017	Delta-wide	GRACE satellite and validated with in-situ measurements
	525	Islam et al., 1999	1979 – 1995	At Mawa gauging station	Single rating curve

Studies underpinning impact map

Table 4: References that contributed to the impact map (Figure 6) of the manuscript.

Reference Study	Contribution to Impact Map
Kabir et al. 2020[6]	Erosion around Hatia Island
Mahmud et al., 2020[7]	Erosion around Meghna estuary
Rashid, 2020[8]	Erosion along Padma river
Ety and Rashid, 2020b[9]	Erosion along lower Ganges
Mullick et al., 2019[10]	Erosion along Sundarban coast
Murshed et al., 2019[11]	Salinity extents in south-west Bangladesh
Ghosh, 2019[12]	Erosion around Sagar Island
BDP, 2018[13]	Salinity intrusion contours and erosion along rivers and coasts
Ahmed et al., 2018[14]	Erosion along coastline
Ahmed et al., 2018b[15]	Erosion around Meghna estuary
Dewan et al., 2017[16]	Erosion along Ganges in Bangladesh
Rahman et al., 2017[17]	Salinity extents in south-west Bangladesh
Hazra et al., 2016[18]	Erosion along Sundarban coastline
Islam et al., 2016[19]	Erosion along Sundarban coastline
Ghosh and Mukhopadhyay, 2016[20]	Erosion in Indian part of delta
Pahlowan and Hossain, 2015[21]	Erosion along coastline
Edmunds et al., 2015[22]	High arsenic levels in Bangladesh
Wilson and Goodbred, 2015[23]	Erosion in Meghna Estuary
Dasgupta et al., 2015[24]	Salinity extents in south-west Bangladesh
Brammer, 2014[25]	Erosion along coastline
Sarker et al., 2014[26]	Erosion along Brahmaputra river
Hossain et al., 2013[27]	Erosion along Ganges in Bangladesh
Sarwar and Woodroffe, 2013[28]	Erosion along coastline
Shearman et al., 2013[29]	Erosion along coastline
Rahman et al., 2011[30]	Erosion along Indian Sundarban coastline
Islam and Gnauck, 2011[31]	Mangrove dieback in Bangladeshi Sundarbans
Islam, 2009[32]	Erosion along Ganges and Brahmaputra in Bangladesh
Datta et al., 2009[33]	High arsenic levels in Bangladesh
Metral et al., 2008[34]	High arsenic levels in Bangladesh and West Bengal
Mikhailov and Dostenko, 2007[35]	Erosion along coastline
Ravenscroft et al., 2005[36]	High arsenic levels in Bangladesh
Tareq et al., 2003[37]	High arsenic levels in Bangladesh and West Bengal
Khan and Islam, 2003[38]	Erosion along Brahmaputra
Sarker et al., 2003[39]	Erosion along Brahmaputra
Allison, 1998[40]	Erosion along coastline
Umitsu, 1997[41]	Erosion around Meghna estuary

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