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A Sustainable Future Supply of Fluvial Sediment for the Ganges-Brahmaputra Delta

Stephen E. Darby, Robert J. Nicholls, Md. Munsur Rahman, Sally Brown, and Rezaul Karim

15.1 Introduction

The world's deltas are facing a major sustainability challenge. Specifically, most of the world's large deltas (24 of 33) are threatened by a combination of rising sea levels and ground surface subsidence, increasing the possibility of submergence for around two and a half million square kilometres

S. E. Darby (✉)
Geography and Environment, Faculty of Social, Human and Mathematical Sciences, University of Southampton, Southampton, UK

R. J. Nicholls • S. Brown
Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton, UK

Md. Munsur Rahman • R. Karim
Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

of land (Syvitski et al. 2009), thus presenting a major issue for approximately 500 million inhabitants. Recent work has warned that the current scale of delta submergence (loss of elevation) is unprecedented in the last 7,000 years (Giosan et al. 2014). It has also been predicted that the extent of flood prone areas in deltas will further increase, perhaps by as much as 50 per cent, as sea levels continue to rise due to anthropogenic climate change (Syvitski et al. 2009).

At one level, understanding of the factors driving relative sea-level rise is well developed. Changes in delta surface elevation are controlled by a balance between rates of (i) eustatic sea-level rise and losses in surface elevation (i.e., natural sediment compaction, as well as accelerated subsidence driven by activities such as groundwater extraction) and (ii) gains in surface elevation as a result of the deposition of (largely) fluvial sediment. What is clear is that, as the only factor that could potentially offset losses in delta surface elevation, a sustainable supply of fluvial sediment is critical in generating the deposition needed to prevent 'drowning' (Ericson et al. 2006; Syvitski et al. 2009). River sediments therefore have considerable economic value, not only as a natural agent of flood mitigation but because deposited river sediments also carry nutrients (carbon, nitrogen, phosphorus) that help maintain agricultural productivity (Jin et al. 2015; Whitehead et al. 2015). As such, these river sediments can appropriately be described as 'brown gold'.

The combined sediment loads (more than 1 gigatonne per year; Islam et al. 1999) from the Ganges and Brahmaputra rivers (note that the Meghna is excluded from consideration as its sediment flux of around 13 million tonnes (Mt) per year is negligible in comparison to either the Ganges or Brahmaputra) have built one of the world's largest and most populous river delta systems (Woodroffe et al. 2006). Under natural conditions, these massive sediment loads would drive sediment deposition on the delta surface at sufficiently high rates (~3.5 mm per year) to compensate for slow sea-level rise and natural compaction-driven subsidence (Goodbred and Kuehl 1999; Wilson and Goodbred 2015). For these reasons, the Ganges-Brahmaputra-Meghna (GBM) delta presents an ideal system to investigate whether climate-driven changes in future fluvial sediment flux could compensate for (or compound) the adverse impacts of accelerated global sea-level rise and anthropogenic subsidence, particularly as the lives and livelihoods of so many people are at stake.

Within this context, this chapter reviews the policy implications arising from new insights, developed through state-of-the-art modelling into the prediction of future sediment loads supplied by the Ganges and Brahmaputra Rivers to the GBM delta. In particular, the implications of the new predictions of future sediment supply are outlined in terms of managing the sediment to maximise its potential for offsetting relative sea-level rise and to ensure that agriculture is able to maximise the value of the natural fertilisation afforded by the nutrients bound to the finer fraction of that sediment load (Jin et al. 2015; Whitehead et al. 2015).

15.2 Prognosis: New Insights

As part of the wider research, a climate-driven hydrological water balance and sediment transport model (HydroTrend; Kettner and Syvitski 2008) was employed to simulate future climate-driven water discharges and sediment loads flowing from the catchments upstream into the GBM delta (see Darby et al. 2015 for a detailed overview). Specifically, HydroTrend was parameterised using high-quality topographic data and forced with daily temperature and precipitation data obtained from downscaled Regional Climate Model (RCM) simulations for the period 1971–2100 (see Chap. 11 and Caesar et al. 2015). Note that the RCM (Jones et al. 2004) has a relatively high spatial resolution (0.22° × 0.22°, approximately 25 km) and covers a large South Asian domain (with rotated pole coordinates of 260° longitude and 70° latitude). This is important because it allows for the development of full mesoscale circulations and thereby captures important regional atmospheric dynamics relevant to the GBM catchments.

The model simulations were run for the period 1971–2100 using observed greenhouse gas forcing for the historical period and the SRES A1B emissions scenario (Nakićenović et al. 2000) for the future period. As discussed in Chap. 11, the SRES A1B scenario represents a medium-high emissions scenario that is consistent with observed carbon emissions over the past two decades and other existing climate modelling. Furthermore, the HadCM3 simulations used to drive the RCM use a perturbed physics ensemble (PPE) approach, whereby key climate model parameters, which have an associated uncertainty, are perturbed within an ensemble of

simulations to produce a range of projections which reflect the uncertainty in the parameters.

The Met Office perturbed versions of HadCM3 with associated HadRM3P simulations for the 130-year period from 1971 to 2100 to create 17 ensemble results. Three members from this ensemble were selected, referred to as the Q0, Q8 and Q16 runs, respectively (see Table 15.1). The Q0 run represents exhibits a mid-range climate sensitivity to the A1B emissions forcing; Q16 has the highest climate sensitivity (i.e., it is the ensemble member that exhibits the highest global temperature response to the A1B emissions forcing); and finally, the Q8 run, although it has similar sensitivity to Q0, exhibits a different precipitation response. Specifically, unlike the other ensemble members, the Q8 run shows a mid-century decrease in precipitation (Table 15.1). The inclusion of the Q8 run therefore enables the impacts on sediment transfer processes of this possible climate response to be considered, even if the likelihood of this response can be considered to be relatively low.

It was found that fluvial sediment delivery rates to the GBM delta associated with these climate data sets were all projected to increase under the influence of anthropogenic climate change, albeit with the magnitude of the increase varying across the Ganges and Brahmaputra catchments (Fig. 15.1). Of the two study basins, the Brahmaputra's fluvial sediment load is predicted to be more sensitive to future climate change. By the middle part of the twenty-first century, model results suggest that sediment loads will increase (relative to the 1981–2000 baseline period) over a range of between 16 and 18 per cent (depending on climate model run) for the Ganges, but by between 25 and 28 per cent for the Brahmaputra. The simulated increase in river sediment supply from the two catchments

Table 15.1 Overview of the change in temperature and precipitation with respect to the annual mean for the 1981–2000 baseline period under the Q0, Q8 and Q16 Met Office RCM runs for the South Asian domain used in this study (for the SRES A1B emissions scenario) (Darby et al. 2015—Published by the Royal Society of Chemistry)

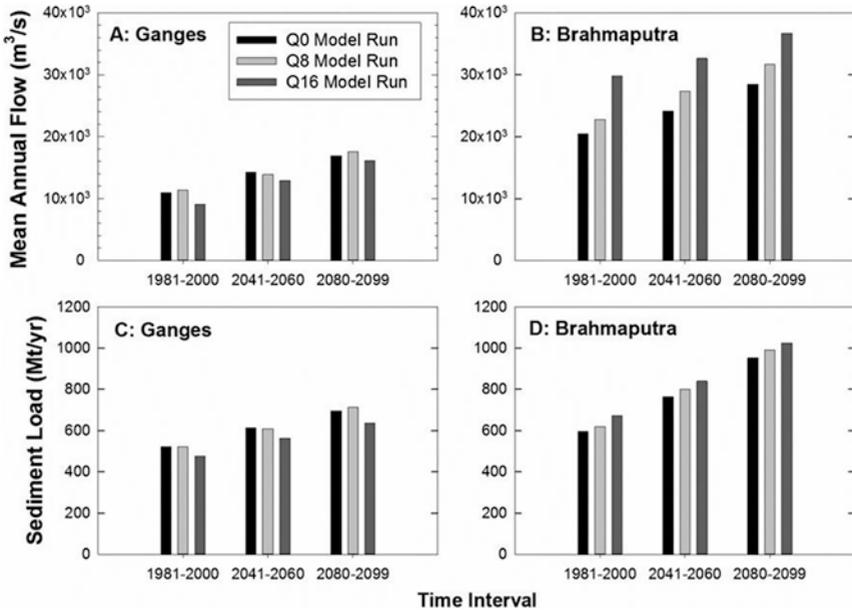| Climate model run	Mid-century (2041–2060)		End of century (2080–2099)	
	Temperature increase (K)	Precipitation increase (%)	Temperature increase (K)	Precipitation increase (%)
Q0	2.3	11.1	4.1	5.1
Q8	2.6	−9.9	4.1	12.7
Q16	2.6	12.2	4.6	29.5

Fig. 15.1 Water discharges and river sediment loads as simulated by HydroTrend for a baseline (1981–2000) and two future (2041–2060 and 2080–2099) 20-year periods for the Ganges and Brahmaputra basins, with HydroTrend forced using climate data for a range of climate model runs (Q0, Q8 and Q16) under the SRES A1B emissions scenario. Subplots (**a**) and (**b**) show the mean annual flow discharges for the Ganges and Brahmaputra basins, respectively, while subplots (**c**) and (**d**) show the mean annual sediment fluxes for the Ganges and Brahmaputra basins, respectively (Darby et al. 2015—Published by the Royal Society of Chemistry)

further increases towards the end of the twenty-first century, reaching between 34 and 37 per cent for the Ganges and between 52 and 60 per cent for the Brahmaputra by the 2090s. The variability in these changes across the three climate change simulations is small compared to the temporal changes (Fig. 15.1).

This research has, therefore, shown that substantial increases in sediment loads are predicted to occur under the medium to high climate change scenarios that were explored. Specifically, the increases in end of century sediment loads that are projected from the Ganges (which range from an additional 161 Mt per year under the Q16 run to 191 Mt per year for Q8) and Brahmaputra (352 Mt per year under the Q16 run to 373 Mt per year

under the Q8 run) amount to a combined increase of between 513 Mt per year and 564 Mt per year. This represents a potential increase of around 50 per cent over and above contemporary sediment loads, raising the question of the best way to manage the additional sediment supply to help alleviate problems in the delta, both today and in the future.

15.3   Policy Implications

Both the present and the additional river sediments that are projected to be supplied to the GBM delta from the Ganges and Brahmaputra catchments represent a resource of significant value through the potential they afford to (i) promote delta building and hence offset relative sea-level rise and (ii) act as vectors of nutrient deposition, offering a 'free' source of natural fertilisation for productive agricultural soils.

However, in some senses, establishing the precise supply of river sediments to the delta in the future is irrelevant as local communities can only derive benefits from those sediments if they are deposited and retained on the delta surface. Large areas of coastal Bangladesh have been protected by polders since the 1960s, excluding sedimentation processes from the land surface therefore not counteracting subsidence due to compaction. In the following sections, the scale of subsidence, the current trends of erosion and accretion, and the potential adaptations that could be implemented to help ensure that the value of these natural sediment services is fully realised are briefly reviewed.

15.3.1   Delta Building

As noted previously, sediment deposition in practice is the only means by which rising sea levels (driven by global warming and accelerated subsidence of the delta surface) can be offset to help slow or prevent relative sea levels continuing to rise in the future. In Table 15.2, reliable subsidence data for the study area (Brown and Nicholls 2015) shows that the median value of the subsidence is 2.6 mm per year, a value that needs to be added to the rate of climatic sea-level rise (SLR) in order to estimate the net relative sea-level rise (RSLR).

Table 15.2 Subsidence rates (mm/year) by geological era within the study area (extracted from Brown and Nicholls 2015)

Geological era	No of data	Min	Max	Mean	Median	Standard deviation
Recent (<1000 y)	16	1.3	10	4	2.6	2.9
Holocene (excluding recent)	6	1.3	4	2.6	2.4	1.1
Pleistocene	0	–	–	–	–	–
Pliocene	0	–	–	–	–	–
All records	22	1.3	10	3.6	2.6	2.6

Despite a number of basin scale and local level anthropogenic interventions in the GBM delta, delta accretion has been found to be the dominant process over the last 200 years, particularly in the Central Estuarine System (CES) of Bangladesh coast, although estimates indicate that the average annual area of land accreted can vary according to the time period and area under analysis (between 3 km²/year and 24 km²/year), as shown in Table 15.3. Consequently, the incoming sediment flux is sufficient to enable RSLR to be offset to some extent.

While both the fine (silts and clays) and coarse (sand) sediment load contributes to delta building, it is generally recognised that it is the sand fraction that is most important (Paola et al. 2011; Giosan et al. 2014; Nittrouer and Viparelli 2014). However, the quantity of coarse sediment which reaches the delta plain (estimated at between 10 and 25 per cent of the total sediment load by Okada et al. 2016) and which potentially contributes to delta building is not simply a function of the overall rate at which sediment is supplied by the rivers from upstream. Instead, in many of the world's deltas, including the GBM, engineering structures and management practices are key factors in controlling local flow dynamics and the exchange of sediment between rivers and the delta plains (Hung et al. 2014; Auerbach et al. 2015). In this respect the way in which the delta's flood defence, irrigation and drainage infrastructure (i.e., the GBM delta's canal and dyke networks) is located, built and operated will play a critical role in determining the potential for sediment deposition and hence delta building.

Although such water engineering infrastructure is essential to protect communities from extreme flooding and to enable productive agriculture,

Table 15.3 Estimates of net accretion within the study area over the last 200 years

Study period	Length of the study (year)	Net accretion (km²)	Accretion rate (km²/year)	Study area	Source
1973–2000	27	510	21	CES	MES II (2001)
1977–2010	34	139	4.08	WES-CES Island	Alam and Uddin (2013)
1940–1963	23	279	12.1	CES	Eysink (1983)
1776–1996	220	2197	9.9	CES	EGIS (1997)
1792–1984	192	1346	7	–	Allison (1998)
1840–1984	144	638	4.4	–	Allison (1998)
2007–2013	6	120	20	Char Island	Hussain et al.(2014)
1776–1943	167	760	4.6	CES	Sarker et al. (2011)
1943–1973	30	1100	42	CES	Sarker et al. (2011)
1973–2008	35	595	17	CES	Sarker et al. (2011)
1750–2000	250	2146	8.58	–	Rashid et al. (2011)
1990–1995	5	16.6	3.1	Bhola Island	Krantz (1999)
1973–2010	37	870	23.5	CES	Sarkar et al. (2013)
2007–2011	4	16.2	3.4	Urir Char	Taguchi et al. (2013)

dyke and canal networks also disconnect rivers from their delta plains and limit the amount of sediment reaching the delta surface. In policy terms, a trade-off must be made between achieving maximum sediment deposition to promote delta building versus the imperative to prevent flooding of agricultural areas and, in so doing, limit sediment deposition. In other deltas around the world, including the Mississippi (Paola et al. 2011; Giosan et al. 2014; Nittrouer and Viparelli 2014) and the Mekong (Manh et al. 2014; Chapman and Darby 2016; Chapman et al. 2016), the balance of that trade-off has been switching to a greater recognition

of the importance of promoting natural sediment deposition for land building as a key adaptation strategy in the face of rising sea levels. This is because policy makers are recognising that it is not in the long-term economic interest to trade-off present-day requirements against the future sustainability of the delta. There are more than ten years of experience in Bangladesh with relatively small-scale tidal river management, or controlled flooding, and sedimentation in polders (Nowreen et al. 2014; Auerbach et al. 2015; Amir et al. 2013). Developing this at a much larger scale is recommended with full consideration of the technical and social challenges. This includes the land-building potential of present and future sediment supply and hence what might be sustainable in the long term.

15.3.2 Natural Fertilisation

Although infrastructure such as dykes and polders can be effective in protecting communities and farmland from flooding, the exclusion of flood water from polder compartments means that sediments are also excluded as well. The exclusion of coarse sediments (see Sect. 15.3.1) is an important consideration in terms of long-term delta building, but the nutrients that are bound to the fine-grained sediments have made deltaic soils and ecosystems some of the most productive on the planet, underpinning the provisioning ecosystem services in deltas (Chap. 1). This link between the sediment and nutrient transport and deposition (Jin et al. 2015; Whitehead et al. 2015) and agricultural productivity (Lázár et al. 2015) has been highlighted specifically in this research. Moreover, recent work has also been undertaken in the similar context of the Mekong delta, where the economic value of the role that fine-grained sediment deposition plays in underpinning agricultural production has been established. In that research, Chapman et al. (2016) and Chapman and Darby (2016) estimated that the nutrients contained within natural sediment deposits provide about half of the fertilisation required to sustain the annual rice crops, amounting to an economic value of $USD 26 million per year in one single province of the Mekong delta. Importantly, they found that poorer farmers were more reliant on natural sediment deposition as they are less able to afford the purchase of artificial fertilisers that can sustain yields when natural sediment

deposition is prevented. Thus, promoting a more natural reconnection of rivers to their delta plains not only has long-term benefits in terms of delta building but also has an immediate benefit for livelihoods, particularly for those who are the poorest and least resilient to fluctuations in fertiliser prices.

15.4 Conclusion

This research shows that, over the course of the remainder of the present century, the supply of fluvial sediment being delivered to the apex of the GBM delta is likely to increase substantially (by around 50 per cent by the 2090s) as a consequence of medium-high anthropogenic climate change. An increase in the climate-driven supply of fluvial sediment to the GBM delta has the potential, through accelerated aggradation on the delta surface, to buffer some of the adverse impacts of climate change that are associated with rising sea levels in the Bay of Bengal and which threaten the vulnerable GBM delta. The projected increase in sediment flux emanating from the GBM delta's sub-continental scale catchments therefore represents a potentially beneficial impact of climate change (for the delta and its inhabitants). However, these potential beneficial impacts of climate change remain subject to uncertainty and can only be realised if more sediment actually reaches the delta. This may not be the case if anthropogenic disturbances within the feeder catchments, notably due to existing and proposed future construction of major dams, result in the delta becoming increasingly disconnected from the sediment supply that sustains it. Disconnection also occurs within the delta due to flood defences and polders built since the 1960s.

In terms of specific policy interventions, the key 'no regrets' adaptation (i.e., an adaptation that is viable irrespective of the actual future trajectory of river sediment loads) that is required is to ensure that the supply of river sediment from the GBM catchments upstream is actually retained on delta surface. This means promoting controlled flooding onto the delta surface (a policy that is consistent with the idea of 'working with the river' and which is increasingly being adopted by other major global delta plans, such as the Mississippi and Mekong), including in poldered areas. Bangladesh has begun to explore this approach with tidal river management, but this

needs to be greatly enhanced to realise. This is necessary not only to help build the delta land surface up in an attempt to offset rising sea levels and subsidence but to enable farmers to benefit from the free nutrients transported by those sediments.

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