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Projections of historical and 21st century fluvial sediment delivery to the Ganges-Brahmaputra-Meghna, Mahanadi, and Volta deltas

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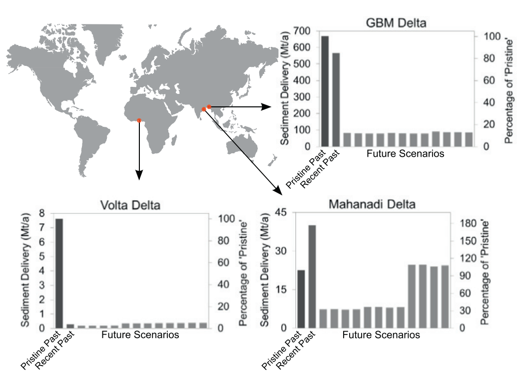
HIGHLIGHTS

- Fluvial sediment delivery is vital for the sustainability of delta environments.
- Sediment supply scenarios were modelled to the GBM, Mahanadi, and Volta deltas.
- Sediment fluxes are largely expected to decline over the 21st century.
- Volta sediment previously declined due to reservoir construction and remains low.
- Basin management should consider risks to the deltas from anthropogenic activities.

GRAPHICAL ABSTRACT



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ABSTRACT

Regular sediment inputs are required for deltas to maintain their surface elevation relative to sea level, which is important for avoiding salinization, erosion, and flooding. However, fluvial sediment inputs to deltas are being threatened by changes in upstream catchments due to climate and land use change and, particularly, reservoir construction. In this research, the global hydrogeomorphic model WBMsed is used to project and contrast 'pristine' (no anthropogenic impacts) and 'recent' historical fluvial sediment delivery to the Ganges-Brahmaputra-Meghna, Mahanadi, and Volta deltas. Additionally, 12 potential future scenarios of environmental change comprising combinations of four climate and three socioeconomic pathways, combined with a single construction timeline for future reservoirs, were simulated and analysed. The simulations of the Ganges-Brahmaputra-Meghna delta showed a large decrease in sediment flux over time, regardless of future scenario, from 669 Mt/a in a 'pristine' world, through 566 Mt/a in the 'recent' past, to 79–92 Mt/a by the end of the 21st century across the scenarios (total average decline of 88%). In contrast, for the Mahanadi delta the simulated sediment delivery increased between the 'pristine' and 'recent' past from 23 Mt/a to 40 Mt/a (+77%), and then decreased to 7–25 Mt/a by the end of the 21st century. The Volta delta shows a large decrease in sediment delivery historically, from 8 to 0.3 Mt/a (96%) between the 'pristine' and 'recent' past, however over the 21st century the sediment flux changes little and is predicted to vary between 0.2 and 0.4 Mt/a dependent on scenario. For the Volta delta,

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catchment management short of removing or re-engineering the Volta dam would have little effect, however without careful management of the upstream catchments these deltas may be unable to maintain their current elevation relative to sea level, suggesting increasing salinization, erosion, flood hazards, and adaptation demands.

1. Introduction

The world's deltas are home to about 500 million people and support significant additional populations outside of their immediate boundaries due to their abundance of natural resources and the economic opportunities these provide (Woodroffe et al., 2006; Ericson et al., 2006). These natural resources include some of the world's most productive agricultural land (Syvitski, 2008), access to fisheries, connected river and ocean transport links, and oil, gas, and coal reserves (Evans, 2012). In addition to their importance to human societies, deltas also provide globally important habitats which can support high biodiversity including rare species, such as the Sundarbans and Bengal Tiger in the Ganges-Brahmaputra delta, India and Bangladesh (Gopal and Chauhan, 2006), and the Irrawaddy River dolphin (Baird and Beasley, 2005). It is therefore crucial to anticipate and assess any changes which threaten the sustainability of delta environments in order to manage delta systems to ensure their sustainable future.

Coastal deltas are low lying regions and there is considerable concern that many of the world's deltas are at risk of drowning by increasing relative sea level due to accelerated subsidence caused by anthropogenic activities on deltas and local expressions of eustatic sea level rise (Syvitski et al., 2009; Syvitski and Kettner, 2011). The relative sea-level rise affecting deltas is buffered by deposition of sediment on the delta surface. This is the only factor that can offset the negative impacts of sea-level rise, and help prevent salinization, flooding, and land loss (Ibáñez et al., 2014). As a first order control on deposition rates, fluvial sediment delivery to deltas is therefore essential to maintain delta areas and functions (Evans, 2012). Indeed, it is thought that the formation of some modern deltas may have been initiated or promoted by anthropogenic catchment influences which increased fluvial sediment delivery, such as deforestation and agriculture (Maselli and Trincardi, 2013).

Knowledge of fluvial sediment fluxes to deltas is clearly crucial for understanding the extent of the threat posed by relative sea-level rise. However, our understanding of historical trends in, and the contemporary status of, fluvial sediment loads to major deltas remains incomplete. In part, this reflects the challenge of measuring sediment delivery to the coastal zone (Meade, 1996), which in turn means that reliable data on sediment fluxes to deltas are relatively limited. Nevertheless, a scientific consensus has emerged that sediment delivery to many of the world's deltas has declined in recent decades. For instance, 20–100% reductions over the 20th century have been shown by Syvitski et al. (2009), driven primarily by reservoir construction.

The anthropogenic interference, as the major driver of the decline in sediment delivery, has in some specific cases likely been exacerbated or offset by climatic change. In some cases, climate change has led to reductions in sediment loads but elsewhere may have contributed to increasing loads in recent decades. For instance, Zhao et al. (2015) shows a decreasing trend in water and sediment delivery for the Yangtze River due to climate change and anthropogenic activities, Wei et al. (2016) and Jiang et al. (2017) show the same trends for the Yellow River and Jiang et al. (2017) show the effects on the Yellow delta, while Darby et al. (2016) show that climate change in the Mekong River basin is reducing cyclone precipitation, associated runoff and therefore sediment fluxes. In contrast, Lu et al. (2013) indicate that climate change would have increased sediment loads in the Minjiang and Zhujiang rivers if it were not for anthropogenic activities, and Cook et al. (2015) show that an increase in extreme climatic events can increase sediment loads. Fluvial sediment fluxes are now thought to be too low to prevent relative sea-level rise for many deltas (Giosan, 2014).

With a few notable exceptions (Gomez et al. 2009, Darby et al., 2015, Fischer et al. 2017, Tessler et al., 2017), studies that evaluate future changes in fluvial sediment delivery to deltas are even fewer than those which have studied either historical trends in, or the contemporary status of, fluvial sediment delivery to the coast. This lack of insight represents a significant challenge as it is not known if deltas can maintain their elevations relative to sea-level rise. To begin to address this important gap, the aim is to develop realistic projections of historic, present, and future fluvial sediment supply to three major deltas: the Ganges-Brahmaputra-Meghna (GBM) in Bangladesh and India; the Mahanadi in India; and the Volta in Ghana (Fig. 1), to assess the trends of sediment supply and their implications. The specific objectives of the research are to:

1) Develop scenarios for sediment fluxes to the three deltas: one scenario representing the 'pristine' past, excluding anthropogenic influences; one for the 'recent' past, mimicking the end of the 20th century; and 12 future scenarios which incorporate pathways of climate and socioeconomic change and reservoir construction;
2) Evaluate model performance in simulating fluvial sediment fluxes to each of the three deltas by using the 'recent' past setup to compare modelled versus observed sediment loads;
3) Application of the model using both the past setups and the 21st century scenarios to project future fluvial sediment fluxes to the three deltas;
4) Consider projected changes in sediment delivery for the three deltas in the context of implications for the sustainability of each delta, including relative sea-level rise.

The scenarios are new in their combination of data, particularly the inclusion of projected future reservoir construction data. The three deltas selected for analysis are the focus of the DECCMA project (Hill et al., this issue) and represent a sample of the world's more populated and vulnerable deltas. While the results will only be valid for these three specific deltas, this analysis provides the opportunity to assess the conclusions within the context of other deltas worldwide.

2. Methods

2.1. The WBMsed model

The model applied in this research is the fully distributed spatially and temporally explicit climate-driven hydrogeomorphic model WBMsed, which is discussed in detail by Cohen et al. (2013, 2014), and interested readers are referred primarily to those publications for further information. WBMsed runs at the global scale and can produce up to daily temporal resolution hydrogeomorphic data such as water and sediment fluxes. For the current research, WBMsed is run at 0.1 degree resolution, which results in catchments of around 15,000 cells for the GBM, 1500 for the Mahanadi, and 3500 for the Volta. Water fluxes are calculated in WBMsed for each grid cell using precipitation, modulated by soil moisture, evapotranspiration, irrigation, reservoir, and groundwater storage, with discharge transported according to channel networks, cell storage times, and floodplain inundation. The key sediment delivery equation in the model is BQART (Kettner and Syvitski, 2008; Syvitski and Milliman, 2007), which empirically estimates

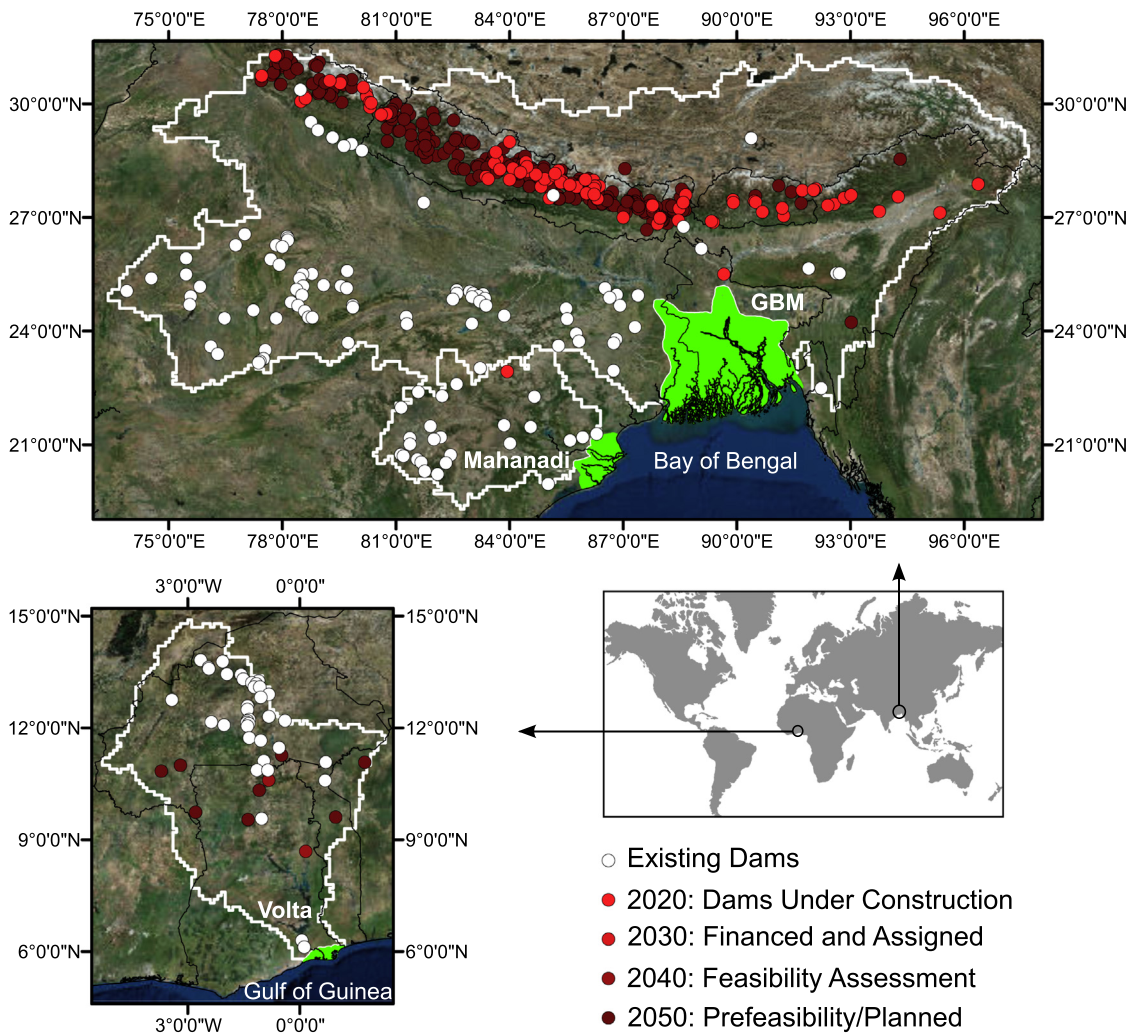

Fig. 1. Location maps for the three delta study areas, including a global location map, the specific extents of each delta area (green, adapted from Tessler et al., 2015), their feeder catchments (white outlines), country boundaries (black outlines), and the locations of existing (Lehner et al., 2011a, 2011b) and planned hydropower reservoirs (Zarfl et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suspended sediment fluxes by accounting for various influences on catchment erosion, deposition, and transport processes:

$$Q_S = \omega B Q^{0.31} A_B{}^{0.5} R T \text{ when } T \geq 2\,^{\circ}C \tag{1}$$

$$Q_S = 2\omega B Q^{0.31} A_B{}^{0.5} R \text{ when } T < 2\,^{\circ}C \tag{2}$$

$$B = (1 - T_E) G L E_H \tag{3}$$

The catchment water discharge (Q in m^3/s) calculated and output by the water balance model is used alongside air temperature (T in °C), basin area (A_B in km^2), catchment elevation change (R in m), lithology (L, unitless), glaciated area (G, unitless), reservoir trapping efficiency (T_E, unitless, discussed below), the anthropogenic factor (E_H, GNP in $US per capita and population density per km^2) to estimate sediment fluxes (Q_S in Mt/a). ω is a proportionality coefficient (0.02 for kg/s or 0.0006 for Mt per year). The B factors are defined in Syvitski and Milliman (2007). Although WBMsed can produce daily estimates of sediment flux, annual sediment loads are estimated here.

The anthropogenic factor (E_H) represents anthropogenic disturbances within the feeder catchments. BQART uses look-up functions derived from an a priori method based on socioeconomic thresholds to account for anthropogenic influences (Syvitski and Milliman, 2007). As shown in Table 1, the relationship is complex depending on population density and GNP per capita. For low population densities anthropogenic activities will not have any major effect on sediment loads. For high population densities, poor populations increase sediment loads, whereas richer populations reduce sediment loads, reflecting significant differences in agricultural practices, land cover, and engineering methods between rich and poor societies.

WBMsed also includes the ability to account explicitly for the effects of sediment trapping by reservoirs (T_E). Large reservoirs are located in a cell on a river network within WBMsed and have a volume property. The volume of a reservoir is used to calculate the modulation of the discharge of water from the reservoir cell, and is also used to calculate the change to sediment fluxes downstream of the cell in which the reservoir is located. Reservoir trapping efficiency is calculated using Brown (1944) for small reservoirs (<0.5 km^3) and Brune (1953) and

Table 1
Multiplicative factor of anthropogenic influence on fluvial sediment fluxes within the BQART equation as implemented in WBMsed.

		Population density		
		<30/km^2	30–140/km^2	>140/km^2
GNP per capita	<$2500	1	1	2
	$2500–$20,000	1	1	1
	>$20,000	1	0.2	0.3

Vörösmarty et al. (2003) for larger water bodies (≥0.5 km^3). The sensitivity of different parameters in WBMsed has been explored in prior studies, including Cohen et al. (2013, 2014).

2.2. Model setup and scenarios of future environmental change

The modelling approach used in the current research is displayed in Fig. 2. Much of the input data to the model is the same as used in Cohen et al. (2013, 2014) as this model setup produces reasonable results for a wide range of environmental situations. The inputs to WBMsed are detailed in Table 2, and those that differ from the Cohen et al. (2013, 2014) inputs are discussed below. The setup used here differs from the Cohen et al. (2013, 2014) studies primarily in that we employ climate, reservoir, and socioeconomic data specific to the three catchments investigated herein and configured to the environmental change scenarios discussed in this section. Note that we employ WBMsed within three specific time periods, each with different key inputs.

Firstly, a ‘pristine’ past run was produced in which it is assumed that there is no anthropogenic influence, removing irrigation and reservoir operations from the model. The ‘pristine’ run was used to drive WBMsed to project sediment fluxes as they would have been before anthropogenic interventions. For the model setup, this means that no reservoirs were included and it was assumed that anthropogenic economic activities and populations were absent. Secondly, a ‘recent’ past run was constructed to represent the environment at the end of the 20th century, in order to model sediment fluxes approximately as they are today. The presented sediment delivery results from the ‘recent’ past run are the average of the 1990–1999 annual data. Finally, scenarios were constructed using different pathways of climate change, socioeconomic change, and reservoir construction to the end of the 21st century. The presented sediment flux results for these scenarios are the averages of annual data during the period 2090–2099, and are used to show the potential changes in sediment delivery to the three deltas over the 21st century under a range of environmental conditions. Note that these scenarios are different to those presented by Kebede et al. (this issue), although they share some of the same concepts and input data.

The climate data used for all model runs were derived from the Met Office Hadley Centre Global Environment Model version 2 - Earth System (HasGEM2-ES) at 0.5 degree resolution, described by Jones et al. (2011). The climate data is not bias corrected due to the global scale of the dataset. The climate data used for the historical ‘pristine’ run was the 1950–1959 time period data, with this 10 years of climate data repeated 7 times to produce a 70 year timeline. The results presented from the ‘pristine’ model run were taken from the final year of the 70 year simulation. While the modelled climate data from the 1950s is not directly equivalent to the climate before significant anthropogenic interference, there are no older spatially distributed datasets available which meet the requirements of the model. Consequently, the 1950–59 period represents a compromise between the goal of driving the model to produce sediment fluxes as they were before anthropogenic disturbance and the reality that earlier data is not fit for purpose. A ‘recent’ historical model run was also set up using the climate data from Jones et al. (2011), but based on the 1990–1999 time period. The 21st century scenarios employed climate projections using Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, and 8.5 from Jones et al. (2011). Each RCP is numbered for the global average radiative forcing level that it stabilises at (4.5 and 6.5), or for the maximum radiative forcing level by 2100 (2.6 and 8.5). However, the path taken up to 2100 is different for each scenario (see van Vuuren et al., 2011).

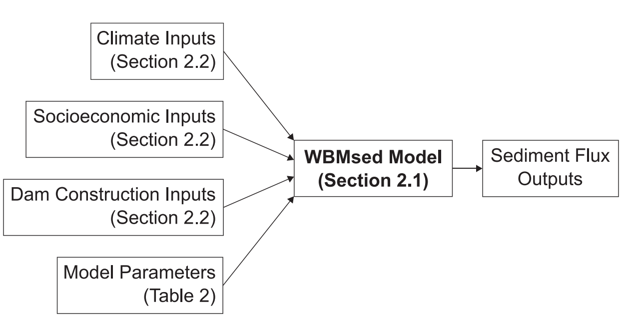

Fig. 2. Flowchart of modelling approach used in the current research. For further detail of WBMsed see Cohen et al. (2013).

Table 2
Relevant inputs to the model WBMsed including the format of input data and global data sources. FAO: Food and Agricultural Organisation.

Input	Format	Data source
Temperature (°C)	Daily grid	Jones et al., 2011
Precipitation (mm)	Daily grid	Jones et al., 2011
Population (per km^2)	Annual grid	Murakami and Yamagata, 2016, IIASA Energy Program, 2015
GNP ($US per capita)	Annual grid	Murakami and Yamagata, 2016, IIASA Energy Program, 2015
Large reservoir capacity (km^3)	Annual grid	Lehner et al., 2011a, 2011b, Zarfl et al., 2015, Grill et al., 2015
Flow network	Static grid	Vörösmarty et al., 2000
Contributing area (km^2)	Static grid	Vörösmarty et al., 2000
Maximum relief (m)	Static grid	Cohen et al., 2008
Minimum slope (°)	Static grid	Vörösmarty et al., 2000
Ice cover (km^2)	Static grid	Cohen et al., 2013
Small reservoir capacity (m^2)	Annual grid	Wisser et al., 2010
Irrigation area (km^2)	Annual grid	Wisser et al., 2008
Irrigation intensity	Static grid	Allen et al., 1998
Irrigation efficiency	Static grid	Allen et al., 1998
Crop fraction	Static grid	Ramankutty and Foley, 1999
Lithology factor	Static grid	Dürr et al., 2005; Syvitski and Milliman, 2007
Soil parameters	Static grid	FAO Soil Map; Melillo et al., 1993
Bankfull discharge (m^3/s)	Grid and recurrence interval constant	Cohen et al., 2013
River bed slope (°)	Constant	Cohen et al., 2013
Floodplain to river flow (m^3/s)	Constant	Cohen et al., 2013

The reservoir data used to create a scenario of reservoir development is taken firstly from the Global Reservoir and Dam database (GRanD, Lehner et al., 2011a, 2011b), a temporally and spatially explicit database which includes all current (as of 2010) dams with reservoirs of over 0.1 km^3 and reservoirs smaller than this where data was available. The ‘pristine’ past run assumes that no dams are present; the ‘recent’ past run includes reservoirs recorded in GRanD as they existed before 1990 or were completed between 1990 and 1999. For all the other future scenarios, the dams recorded in GRanD are employed along with the future reservoirs from the projected dam database of Zarfl et al. (2015), which includes information on planned and under construction hydropower dams with over 1 MW capacity (shown in Fig. 1). As Zarfl et al. (2015) do not include reservoir volume in the projected dam database, the reservoir volumes required for input to WBMsed were calculated from potential generating capacity using the relationship established by Grill et al. (2015). It is assumed that all of the dams included in the database are implemented by the year 2050, with the locations and timeline shown in Fig. 1. The reservoir volumes for the three delta's basins at each time step are shown in Fig. 3, which indicates a large rise (240%) in reservoir volume for the GBM, but only a small increase for the Mahanadi (0.6% change) and Volta (0.7% change).

The socioeconomic data (GNP and population) used is from Murakami and Yamagata (2016), who downscale country scale population and GNP data from the International Monetary Fund (up to 2010) and IIASA Energy Program (2015) (after 2010) to a 0.5 degree

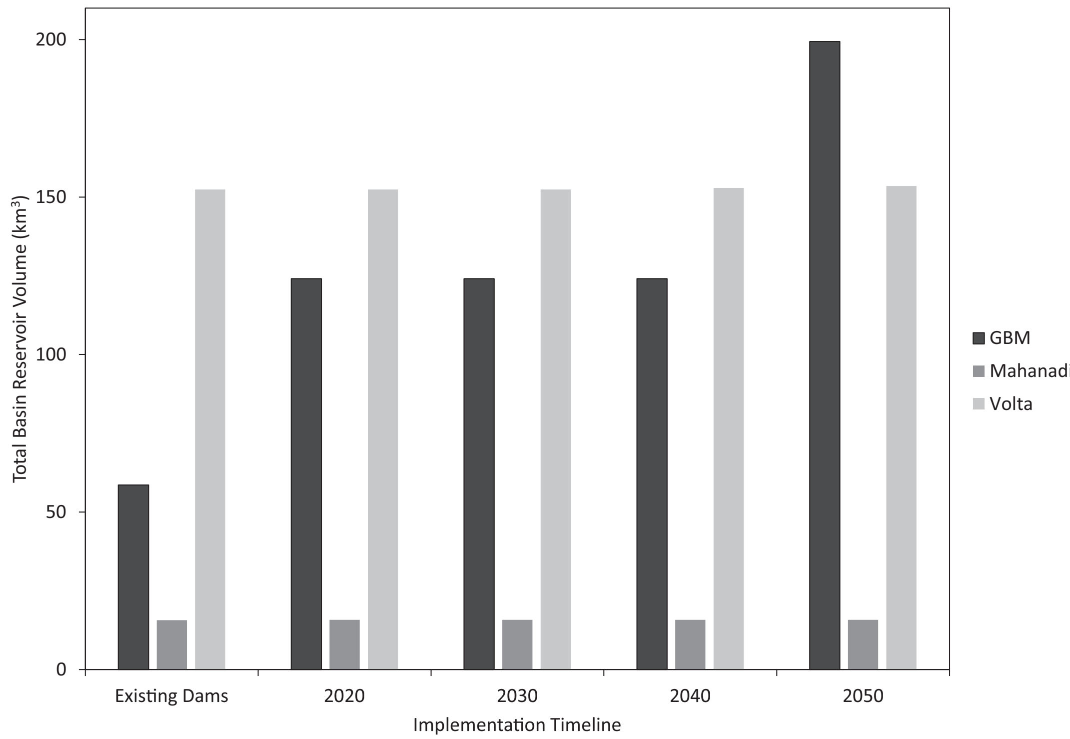

Fig. 3. Total volumes of reservoirs in the upstream basins of the GBM, Mahanadi, and Volta deltas at each step of the dam implementation timeline. Existing dams from the GRanD database (Lehner et al., 2011a, 2011b), potential future dams from Zarfl et al. (2015) with reservoir volumes calculated using Grill et al. (2015) as described in text.

resolution global grid. The decadal socioeconomic data from Murakami and Yamagata (2016) was then linearly interpolated temporally to give annual values. The 'pristine' past run assumes no human populations and therefore no GNP; the 'recent' past run uses International Monetary Fund country data downscaled by Murakami and Yamagata (2016) for 1990–1999; the scenarios use country data for Shared Socioeconomic Pathways (SSP) 1, 2, and 3 from IIASA Energy Program (2015) downscaled by Murakami and Yamagata (2016) and assuming sustainable progress (SSP1), dynamics as usual (SSP2) or a fragmented world (SSP3).

The combinations of climate (four RCPs) and socio-economic (three SSPs) pathways therefore lead to the development of a total of 12 future scenarios that were explored for each of the three study catchments, with the reservoir construction scenario in each case being embedded within the timelines for each of the 12 future scenarios. Each SSP and RCP combination has a different likelihood of occurrence (van Vuuren et al., 2014; Riahi et al., 2017) due to the lower probability of, for instance, maintaining low levels of greenhouse gas (GHG) emissions and atmospheric concentrations with a poor, populous global community, or reaching a high level of the same in a less populated world. However, in this work none of the scenarios are excluded so the result is 12 scenarios spanning a range of future climate change and socioeconomic pathways. The key differences between scenarios are detailed in Table 3.

2.3. Evaluation of WBMsed performance

WBMsed has been successfully applied at the global scale (Cohen et al., 2014). To assess its suitability for application in this current research WBMsed was run as described above (the 'recent' past run) and the model water and sediment fluxes were then compared with observed data from each of the three deltas. Considering the availability of water discharge data, WBMsed was set up as the 'recent' past run from 1980 to 2000 so that the observed and corresponding modelled water discharge data could be compared. For the combined Ganges and Brahmaputra discharge (only 1 year of data was available for the Meghna) the comparable time period was January 1980 to March 1996; for the Volta the comparable time period was January 1980 to December 1984; and for the Mahanadi system the only observed water discharge data available was for the Brahmani January 1971 to December 1971, which was insufficient to perform an effective evaluation.

The water discharge comparison for the GBM and the Volta is presented in Fig. 4. The data shows that, considering the modelled climate inputs, the hydrological representation of the GBM and Volta catchments in WBMsed is acceptable, with discrepancy ratios approaching 1 for both rivers. For the GBM, WBMsed generally underestimates the peak discharges which could lead to an underestimation of sediment fluxes. For the Volta, the observed water discharge time series is only

Table 3
Differences between the 12 constructed potential future scenarios. Note that the reservoir construction scenario as detailed in the text is embedded within each of these 12 scenarios.

		Representative concentration pathways			
		RCP8.5	RCP6.0	RCP4.5	RCP2.6
Shared socioeconomic pathways	SSP1	High climate change, low socioeconomic challenges	Medium-high climate change, low socioeconomic challenges	Medium-low climate change, low socioeconomic challenges	Low climate change, low socioeconomic challenges
	SSP2	High climate change, medium socioeconomic challenges	Medium-high climate change, medium socioeconomic challenges	Medium-low climate change, medium socioeconomic challenges	Low climate change, medium socioeconomic challenges
	SSP3	High climate change, high socioeconomic challenges	Medium-high climate change, high socioeconomic challenges	Medium-low climate change, high socioeconomic challenges	Low climate change, high socioeconomic challenges

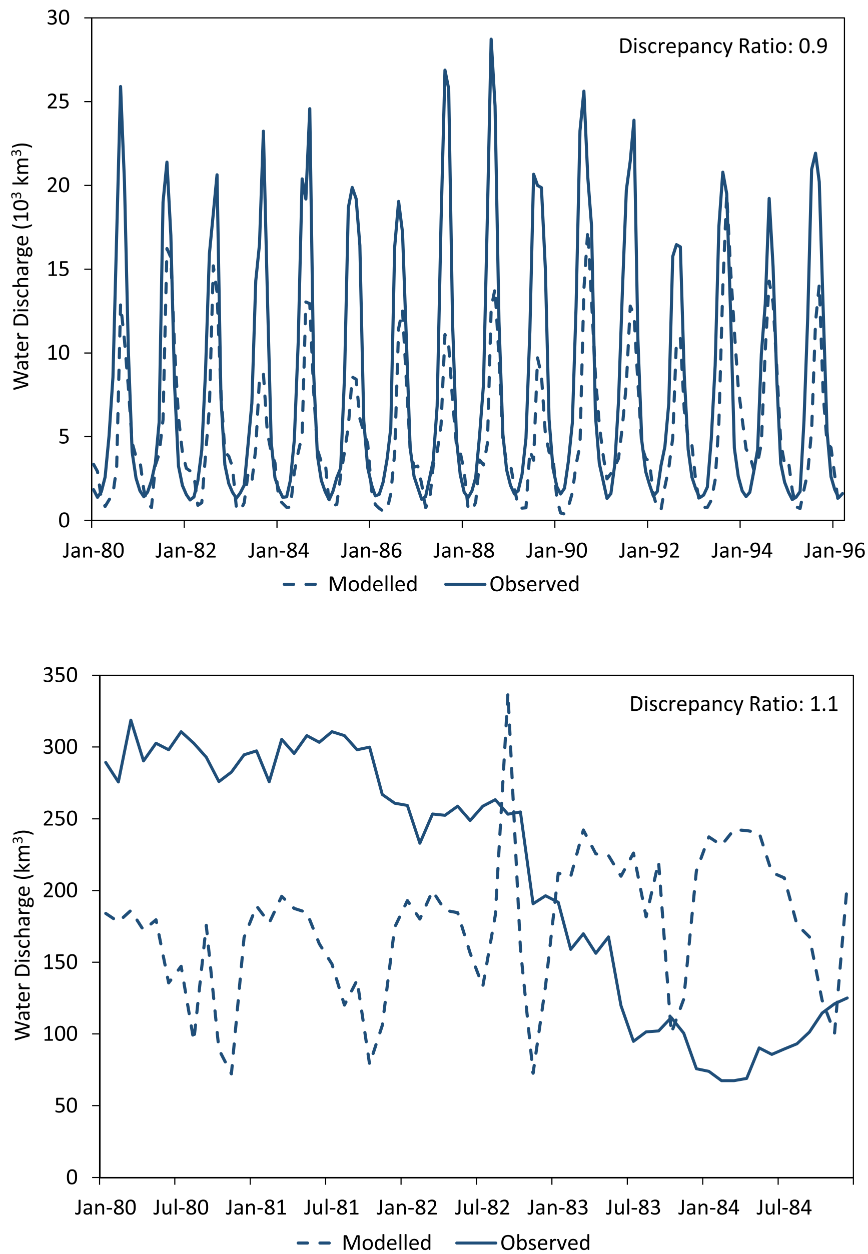

Fig. 4. Comparison of monthly observed and modelled water discharge data for the GBM (top panel, comprising combines Ganges and Brahmaputra water fluxes) and the Volta (bottom panel). The discrepancy ratio is the average of modelled/observed data for each month. Note different x and y axes.

5 years long and appears to cover a period of change, so limited information can be derived from analysis. However, both the overall magnitude and seasonal variability of the modelled data for the Volta appear to be appropriate, although additional observed data would be needed to confirm this.

The comparison between the modelled and observed sediment flux data for the 1990s is shown in Table 4. Note that in these comparisons, the modelled estimates of sediment flux are taken from the locations of the gauging stations closest to the apices of the deltas where such stations are available. However, note that in Section 3 we use sediment flux data for the apex of each delta, as listed in Table 4. It is evident from Table 4 that sediment delivery to all three of the deltas is underestimated, but the discrepancies between the observed and simulated data are relatively small for the GBM and Mahanadi. On average across the deltas, the overall fit discrepancy ratio is −0.34. The best estimates of observed sediment fluxes are used for comparison, however the other available observed data is shown in Fig. 5. These results afford confidence in the use of the model for projecting sediment fluxes to the three deltas.

The GBM delta is one of the better studied systems globally and the observed sediment data used here is from the Bangladesh Water Development Board, as detailed by Rahman et al. (this issue) who also discuss previous estimates of fluvial sediment fluxes to the GBM delta. It should be noted that the observed data is derived from measurements made on the Ganges River at Hardinge Bridge, located around 150 km downstream of the delta apex, in the years 2001, 2004, and 2008. On the Brahmaputra River the gauging station is at Bahadurabad, which is located near the apex, and monitoring took place during the periods 1968–1970, 1972–1974, 1978–1995, and 2000–2001. The differences in timing between the measured and modelled data for the Ganges are small. However, the period of measurement for the Brahmaputra is longer and is primarily earlier than the modelled data. Considering

Table 4
Comparison of simulated (for 'recent' historical scenario; averaged 1990–1999) versus observed sediment flux (Qs) data for the three deltas that are the focus of this study. Bold 'Observed Qs' values are most reliable and comparable ('Best Estimate' in Fig. 5), and used for comparison. The normalised discrepancy ratio is calculated as log (simulated Qs/observed Qs), such that a value of 0 represents a perfect match between simulated and observed data, 1 represents an order of magnitude overestimate, and − 1 represents an order of magnitude underestimate.

	Latitude and longitude of apices	Coordinates of gauging stations	Observed Qs (Mt/a)	Simulated Qs (Mt/a)	Normalised discrepancy ratio
GBM	Ganges: 24.85, 87.95 Brahmaputra: 25.25, 89.75 Meghna: 24.35, 91.15	Ganges: 24.05, 89.05 Brahmaputra: 25.35, 89.75	**670 (Ganges and Brahmaputra, Rahman et al., this issue, Meghna not included due to sparse data)** 1037 (Ganges and Brahmaputra, Islam et al., 1999) 1060 (Milliman and Syvitski, 1992) 1670 (Milliman and Meade, 1983)	596	−0.07
Mahanadi	Mahanadi: 20.45, 85.85 Brahmani: 20.85, 86.15 Baiterani: 21.25, 86.15	Mahanadi: 20.65, 84.75 Brahmani: 20.85, 86.05	**51.1 (Mahanadi and Brahmani, Panda et al., 2011, Baiterani data unavailable)** 2 (Mahanadi, Milliman and Meade, 1983) 15.1 (Gupta et al., 2012) 30 (Mahanadi, Chakrapani and Subramanian, 1990) 60 (Mahanadi, Milliman and Syvitski, 1992)	35	−0.17
Volta	6.55, 0.05	Gauging location unavailable	**1.6 (Milliman and Farnsworth, 2011)** 0 (Milliman and Syvitski, 1992) 14 (Boateng, 2009)	0.3	−0.77

the trends discussed by Rahman et al. (this issue), the difference in timing between the measured and modelled data could cause the measured sediment flux to be artificially greater than the modelled, potentially accounting for some of the model bias seen here.

For the Mahanadi delta, the measurements of sediment load are taken from the Mahanadi and Brahmani River for the years 1993–2003, which almost exactly overlaps with the modelled data time period. The sediment flux of the third river feeding the Mahanadi delta, the Baiterani River, has not been monitored but is assumed to be small. The Mahanadi River was gauged at Tikarpara, 200 km from the river mouth and upstream of the delta. The Brahmani River was gauged at Jenapur, 100 km from the river mouth at around the apex of the delta. These observations were chosen due to the time period being comparable to that simulated by the model, however, there are other sediment flux data available for the Mahanadi delta system. For instance, Gupta et al. (2012) report measurements which were taken from the same locations as Panda et al. (2011) but for the period 1973–2010 for the Mahanadi River, and for 1980–2010 for the Brahmani River. The combined average annual sediment flux of the Mahanadi and the Brahmani derived for the longer time period was 15.1 Mt/a, which compares to the value of 51.1 Mt/a for the 1993–2003 period. That these estimates do not corroborate is indicative of the observational uncertainty surrounding sediment delivery estimates, but may also highlight the natural variability in sediment fluxes over annual and decadal timescales on these rivers.

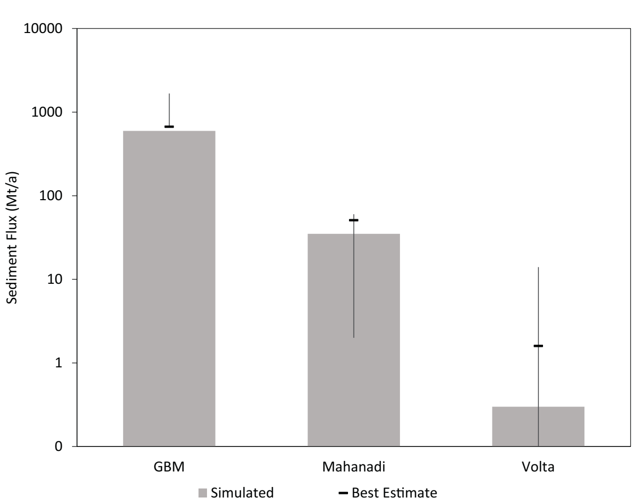

Fig. 5. Range of observed sediment load data (see Table 4 for references) compared with sediment data simulated by WBMsed.

The Volta River sediment data is from Milliman and Farnsworth (2011), which provides no information on dates or locations of measurements. The poor result for the Volta may be due to spatial and temporal distance between the observed and simulated values, although this cannot be confirmed due to a lack of information on the observed value. The Volta River system is not well studied, so there are fewer estimates of fluvial sediment flux available for comparison than for the GBM and Mahanadi river systems, which results in uncertainty over the accuracy of the available estimate. However, it must be assumed that the Volta sediment discharge is underpredicted, although it is thought that fluvial sediment supply to the delta was reduced by over 99% due to the construction of the large Akosombo dam in the early 1960s (Ly, 1980), which means that the extremely low simulated 'recent' sediment flux is reasonable.

3. Results: fluvial sediment fluxes from WBMsed

3.1. GBM delta

Model projections of fluvial sediment delivery to the GBM delta are shown in Fig. 6. For the GBM delta, the simulations exhibit a clear picture in which the 'pristine' scenario shows the highest mean annual sediment load (669 Mt/a), declining to a value of 566 Mt/a for the 'recent' past scenario (a decline of 15%), to much lower values (in the range 79–92 Mt/a, depending on scenario) for the 12 future scenarios, the latter representing a decline in sediment loads between 'pristine' values and the end of the 21st century of some 88% when averaged across the 12 future scenarios. The low variance between the results of the future scenarios is notable and indicates that the variability embedded within the scenarios has little impact on the degree to which fluvial sediment delivery is predicted to change by the end of the 21st century. This lack of variation between the future scenarios is because the main factors causing the reduction in sediment delivery, socioeconomic changes and particularly reservoir construction, occur in all scenarios.

Rahman et al. (this issue) show that the sediment delivery to the GBM system is currently declining by around 10 Mt/a, which is around double the rate projected here (4.74–4.87 MT/a over the 21st century dependent on scenario). This comparison suggests that the decline in sediment fluxes will slow from the rate observed in the recent past to that projected over the coming decades. The reduced rate of sediment flux decline over the 21st century could be due to declining rates of dam and other engineering construction, as the optimal sites for large projects (which intercept large volumes of sediment) are exhausted.

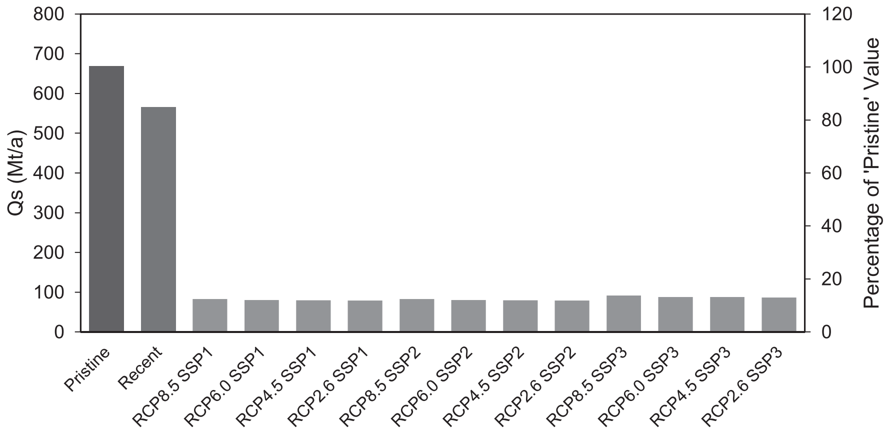

Fig. 6. Projected fluvial sediment fluxes (Q_S) delivered to the GBM delta, as modelled under 2 past and 12 future scenarios described in Section 2.2. The 'pristine' data was the annual value from a single year once the sediment output had stabilised; the 'recent' data was the average of the annual data 1990–1999; the scenario data were the average of the annual data 2090–2099.

These results indicate that sediment delivery to the GBM delta was much higher before more recent anthropogenic interference. The large decrease in sediment delivery seen in all the GBM delta scenarios is caused mainly by the socioeconomic changes projected for this delta system combined with, to a lesser extent, reservoir construction. The reason that the socioeconomic change is the dominant influence in these simulations relates to the substantial projected increases in GNP in the catchment over the 21st century, regardless of socioeconomic pathway. Consequently, the GBM delta catchments move from having the highest positive influence on sediment delivery due to socioeconomic influence (see Table 1) to having a negative influence in all SSPs over the course of the 21st century, resulting in a reduction of sediment fluxes by over a factor of 6 on average due to socioeconomic change, even before the effects of reservoir construction are considered.

In contrast to the influences of socioeconomic change and reservoir construction, climate change causes a small increase in sediment delivery to the GBM delta, as in all three deltas studied here, but the climate change signal is much smaller than the direct anthropogenic interference. The increase in sediment flux due to climate change is 15% on average over the 21st century, which is lower than the increases projected by Darby et al. (2015) of 34–37% for the Ganges and 52–50% for the Brahmaputra. There are several reasons which could explain the discrepancy: Darby et al. (2015) use different climate data and scenarios to this current research, which may lead to different outcomes for fluvial sediment fluxes. Furthermore, Darby et al. (2015) use the model HydroTrend which is not spatially distributed, unlike WBMsed, so this current research may represent an advance in the spatial representation of the effects of 21st century climate change on sediment delivery to the GBM delta.

The results for the GBM delta projections highlight a long-term reduction in sediment load: sediment delivery is estimated to have been higher in the 'pristine' past with no anthropogenic influences than it has been in the 'recent' past, and sediment delivery is projected to decrease still further under a variety of future environmental change scenarios. The differences between the climate and socioeconomic pathways investigated here do not have a noticeable impact on the decline in sediment fluxes. Although there has already been a decrease in sediment fluxes relative to the 'pristine' scenario, there is still the potential for large decreases in sediment from the current situation due to further anthropogenic activities. If the reduction in sediment delivery projected here were to occur, it could have important consequences for the stability and sustainability of the GBM delta system. The projected changes are particularly important for the GBM delta as it is the only delta studied here with information available on its current state. These assessments show that some parts of the delta, particularly the Meghna estuary, are accreting, on average at a rate of 17 km^2/a over the last 50 years (Akter et al., 2016). This accretion is threatened if the projected fall in sediment delivery occurs.

3.2. Mahanadi delta

The simulations of fluvial sediment delivery to the Mahanadi delta are shown in Fig. 7. These results show a different trend to the GBM delta, with a substantial estimated increase in fluvial sediment delivery (from 23 to 40 Mt/a, a 77% increase) between the 'pristine' and 'recent' past scenarios. The fluvial sediment flux projections for the future scenario model runs show a decrease when compared to the 'recent' past data and a decrease for most of the scenarios (8 of 12) when compared to the 'pristine' past. However, the projections for the Mahanadi show more variability by scenario and some of the future scenarios (4 of 12) have projected sediment fluxes that are comparable to the 'pristine' past data. For the individual scenarios the change between the 'pristine' past and the scenarios varies between 32% (lowest is for the scenario using RCP4.5 and SSP1) to 110% (highest is for the scenario using RCP6.0 and SSP3).

For the Mahanadi, the initial increase in projected fluvial sediment delivery between the 'pristine' and 'recent' past scenarios is caused by socioeconomic change. Specifically, in the 'recent' past scenarios, the Mahanadi delta basins are represented as having poor, dense populations which has the effect of doubling sediment delivery when compared to 'pristine' conditions, in which there are no anthropogenic populations and therefore no socioeconomic influence on sediment fluxes. The increase in sediment seen between the 'pristine' and 'recent' past scenarios occurs despite dam construction in the basin, because the effect of the socioeconomic changes outlined previously outweighs the specific effects of additional sediment trapping in reservoirs. For the Mahanadi's future scenarios, the decrease in projected sediment fluxes when compared to the 'recent' past is likewise induced mainly by changes in socioeconomic state, as GNP per capita increases over the 21st century causing the anthropogenic influence on sediment flux to become negative.

The variations in projections for the Mahanadi's future scenarios arise from the different levels of socioeconomic change between scenarios. In those future scenarios which use SSP1 and SSP2, the socioeconomic state of the basins feeding the Mahanadi delta crosses two thresholds due to their increasing GNP per capita (see Table 1), causing their anthropogenic factor value to change from the highest to the lowest possible over the course of the 21st century. In those future scenarios which use SSP3, however, only one socioeconomic state threshold is crossed (from high to medium), so sediment delivery decreases

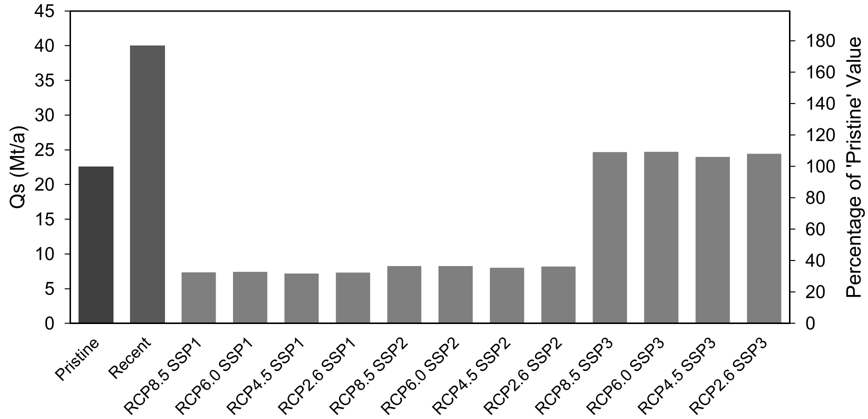

Fig. 7. Projected fluvial sediment fluxes (Q_S) delivered to the Mahanadi delta, as modelled under 2 past and 12 future scenarios described in Section 2.2. The 'pristine' data was the annual value from a single year once the sediment output had stabilised; the 'recent' data was the average of the annual data 1990–1999; the scenario data were the average of the annual data 2090–2099.

noticeably less in the scenarios using SSP3 than in those using SSP1 and SSP2, when compared with the 'recent past' scenarios.

Modest reservoir construction is projected for the basins feeding the Mahanadi delta over the 21st century, and climate change, as in all the deltas studied here, has a small positive influence on sediment delivery, on average 15% over the 21st century. It is the small positive effect of the climate changes, combined with the negative influences of reservoirs and irrigation, which causes the four future scenarios incorporating SSP3 to project slightly higher sediment fluxes as compared to the 'pristine' run. The increase in sediment delivery between the 'pristine' past and some future scenarios is forced mainly due to the temperature increase between the 1950s and 2090s climate data, which has a positive effect on sediment fluxes and is not completely offset by the negative influences of reservoirs and irrigation. Temperature increases (with constant precipitation) lead to an increase in sediment production efficiency, contributing to increased sediment fluxes, however higher temperatures also lead to greater evaporation and therefore reduced water discharge which reduces the sediment transport capacity of fluvial systems. The sediment delivery results for the Mahanadi basin show that sediment fluxes are estimated to have increased when compared to a 'pristine' past, but that they are projected to decline over the course of the 21st century. The decreases are projected to bring fluvial sediment delivery to the Mahanadi delta back down to values at or below the 'pristine' state.

3.3. Volta delta

The results of the projections of sediment delivery to the Volta delta are shown in Fig. 8. The Volta exhibits a different pattern of sediment flux changes to both the GBM and the Mahanadi. There is an estimated decrease in fluvial sediment delivery of 96% (from 8 to 0.3 Mt/a) between the 'pristine' and 'recent' past scenarios, and the changes from the 'recent' past to the future projections are negligible and vary between 0.2 and 0.4 Mt/a (2-5% of the 'pristine' value) dependent on scenario. Of the future scenarios, 8 of 12 (those using SSP2 and 3) project a fluvial sediment flux that is slightly higher than the 'recent' value, whereas for the other 4 scenarios (using SSP1) the future states display fluvial sediment fluxes that are lower than the 'recent' condition.

The extremely large decrease between the 'pristine' and 'recent' sediment delivery values is due to the construction of the Akosombo dam, which was opened in 1965 and produced the largest anthropogenic reservoir in the world by surface area. This single reservoir is thought to have reduced the sediment delivery downstream by a factor of 10 or more (Ly, 1980). The changes in sediment delivery between the 'recent' past and the end of the 21st century are due to the combination of socioeconomic and climate change, as well as additional reservoir construction. Climate change causes a small increase in sediment flux of 0.08 Mt/a on average, whereas reservoir construction forces a negligible decrease on the order of 0.0005 Mt/a. The very small influence of

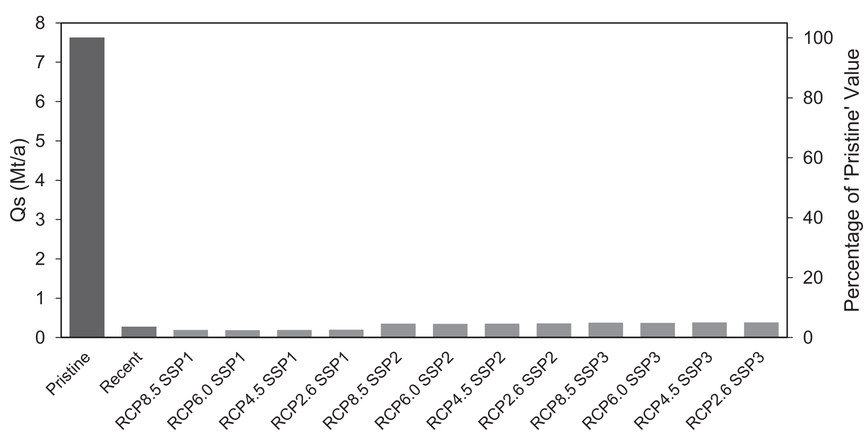

Fig. 8. Projected fluvial sediment fluxes (Q_S) delivered to the Volta delta, as modelled under 2 past and 12 future scenarios described in section 2.2. The 'pristine' data was the annual value from a single year once the sediment output had stabilised; the 'recent' data was the average of the annual data 1990–1999; the scenario data were the average of the annual data 2090–2099.

additional reservoirs is due to the overwhelming influence of the Akosombo dam cutting off changes in the catchment from influencing the river below the dam.

The differences in results between the scenarios are primarily due to different socioeconomic changes, with minimal (0.02 Mt/a) variation arising from differences between the climate change pathways. The future scenarios incorporating SSP1 and SSP2 experience a single socioeconomic state change due to increasing GNP (see Table 1) in the 2090s. The difference between these scenarios is that those using SSP1 experience the socioeconomic change, reducing sediment yields, at the beginning of the 2090s, leading to lower sediment fluxes than in the 'recent' past. In comparison, those scenarios using SSP2 experience the socioeconomic change at the end of the 2090s. As the values shown in Fig. 8 are decadal averages, the difference in the timing of socioeconomic change affects the results. The scenarios using SSP2 therefore show an increase in sediment delivery, although the increase is smaller than in those scenarios using SSP3. Finally, those scenarios using SSP3 experience no significant socioeconomic change, so the increase in sediment flux seen in these scenarios from the 'recent' past value is due to the positive influence of climate change outweighing the negative influence of additional reservoir construction during the 21st century.

3.4. Summary of results

Fluvial sediment delivery to the GBM, Mahanadi, and Volta deltas is estimated to have changed historically in response to shifting environmental conditions, specifically climate change and anthropogenic activities, from 'pristine' (pre-human interference) to 'recent' past conditions. Mean annual sediment loads likely responded by declining for the GBM (by 15%, from 669 Mt/a to 566 Mt/a) and Volta (by 96%, from 8 Mt/a to 0.3 Mt/a) deltas, but increasing for the Mahanadi (by 77%, from 23 Mt/a to 40 Mt/a). Additionally, we have shown that fluvial sediment delivery to the GBM and Mahanadi deltas is projected to decrease over the course of the 21st century in the average of the projected scenarios, while the Volta delta sediment supply can hardly fall further.

For the GBM, the sediment flux by the end of the 21st century is 83 Mt/a, 12% of the 'pristine' value, with a range of 79–92 Mt/a across the scenarios. For the Mahanadi, the end of 21st century sediment delivery is 13 Mt/a, 59% of the 'pristine' value, with a range of 7–25 Mt/a between scenarios. For the Volta, the average sediment flux by the end of the 21st century was 0.3 Mt/a, 4% of the 'pristine' value, with a range of 0.2–0.4 Mt/a between scenarios. The severity of the decrease was dependent on the future scenario and the largest differences between scenarios were caused by the different socioeconomic pathways. Climate change appears to have little impact on sediment fluxes in these three basins.

4. Discussion

The factors which change between the 'pristine' and 'recent' past model runs are mostly incorporated in the proxy for anthropogenic influences (discussed in Section 2.1, Table 1). The factors not represented by the anthropogenic factor are the presence of reservoirs and irrigation, which both decrease sediment delivery due to sediment retention and water abstraction, respectively. The anthropogenic factor in the basins feeding the GBM delta for the 'recent' past is the maximum possible, assuming the presence of poor, high density populations which increase sediment delivery compared to 'pristine' conditions. The combination of input factors has resulted in a decrease from the 'pristine' to 'recent' past sediment delivery values, suggesting that the negative influence of reservoir construction, and to a lesser extent irrigation, has overwhelmed the historical positive influence of other anthropogenic activities on sediment delivery. For the Mahanadi delta, although it may currently have higher sediment delivery than in a 'pristine' state, there are likely additional pressures on the delta due to anthropogenic interference which were not present in the 'pristine' past. In the case of the Volta delta, a single large dam on the main river essentially stopped sediment supply in the 1960s and prevents changes in sediment processes in the upstream catchment from being adequately transmitted to the delta.

The increasing pressure of reduced sediment load may threaten the sustainability of the three deltas, more so for the GBM than the other deltas due to the large projected decrease in sediment delivery with little variation across scenarios. The Mahanadi shows some variation in sediment flux projection between scenarios, while the long-term sustainability of the Volta delta has already been compromised. These projections show that the deltas are in different situations with regards to their future sustainability. The GBM appears to be the most threatened, considering the history of past sediment flux reductions and the magnitudes of the future decreases projected, however the Mahanadi is also projected to suffer sediment delivery reductions, albeit to a lesser and more uncertain extent. The Volta has already seen such a large decrease in sediment delivery that it is likely that the system is currently now unsustainable, and the projected future changes will not have a significant impact either in increasing or decreasing sediment fluxes and therefore sustainability.

However, considering that the cause of the potential sediment flux reductions over the 21st century is direct anthropogenic interference in the catchments, not global climate change, there is also the potential to prevent or appropriately manage any fall in sediment delivery to the deltas to mitigate any destabilising effects. Prevention of the projected reduction in sediment fluxes could be achieved by, for instance, managing reservoir construction and operation to decrease sediment trapping. The level of threat depends on the, largely unknown, current state of the deltas and the links between this current state and fluvial sediment delivery. While this research has presented 'recent' past projections of sediment delivery, it is unknown whether these 'recent' past sediment fluxes are adequate to maintain the deltas in a morphological and area sense under sea-level rise and subsidence. It is possible that these 'recent' past sediment fluxes were not adequate to sustain the delta system, particularly for the GBM and Volta deltas, and that the deltas are currently in a state of degradation, or that environmental changes in the first part of the 21st century have already reduced sediment delivery to below a sustainable level. It is worth noting that the GBM delta still appears to be significantly accreting in the Meghna estuary (Akter et al., 2016), while the Volta delta has experiences widespread and significant coastal erosion over the last few decades (Appeaning Addo et al., 2018). The current state of the Volta in particular is similar to the Nile (Sharaf El Din, 1977; Bohannon, 2010; Darwish et al., 2017) in that the sediment supply has been all but eliminated due to reservoir construction.

While the results provide projections of sediment delivery within the modelling framework, the following limitations have to be kept in mind. WBMsed is a global model with relatively coarse resolution inputs, so while it provides reasonable results across the globe it does not necessarily take into account local inputs and processes. This modelling setup means that the results should be taken as indicative of likely directions and magnitudes of change rather than precise and accurate predictions of past, current, and future sediment fluxes. An additional factor is that the projected environmental changes have never before been observed and so there is no way of verifying the simulated potential response of fluvial systems. This situation is particularly true for the projected socioeconomic changes, which are globally unprecedented and therefore represent a leap into the unknown for fluvial and other earth systems.

5. Conclusions

This research has shown that the three deltas studied, the GBM, Mahanadi, and Volta, have contrasting trajectories of fluvial sediment fluxes and are therefore in different situations with regards to their current and future sustainability of fluvial sediment delivery. The GBM has already experienced a reduction in sediment delivery, and while it appears that the delta is still accreting this situation is likely to change with the large decreases in sediment delivery projected over the 21st century. The Mahanadi, in contrast, has seen an increase in sediment fluxes and so it is assumed, for lack of conflicting information, that the delta is not currently eroding. The projections of future sediment delivery to the Mahanadi depend primarily on the socioeconomic pathway followed, which suggests that the sustainability of the Mahanadi depends on anthropogenic activities yet to occur and could be compromised during the 21st century. Finally, the Volta has already seen an extreme reduction in sediment delivery to the delta, such that future environmental changes have little further effect. Without significant interventions the Volta's delta will continue to erode.

The lines of future work to pursue with this research are many and varied, and will evolve with improved observed data, advancing projected input datasets and model development. For instance, considering the limited and uncertain observed data, remote sensing could be used to verify model results in future works. Remote sensing applications for sediment mapping are well established (e.g. Curran and Novo, 1988; Nellis et al., 1998; Chu et al., 2012; Umar et al., 2018), and are based on identifying the spectral signature changes of water bodies with a range of sediment concentration (Hudson et al., 2014; Lymburner et al., 2016). This research on future sediment delivery could support further work on relative sea-level rise in deltas, such as that by Tessler et al. (2017), to develop a more complete perspective on delta sustainability. In addition, the WBMsed model has undergone recent developments which have the potential to improve future work on modelling fluvial sediment delivery, in particular the introduction of a new land use parameter which improves the spatial representation of the anthropogenic influence, as well as on the original categorical nature of anthropogenic influence (detailed in Table 1). While WBMsed is a hydrogeomorphic model only the output sediment fluxes have been analysed here, however there is the potential to investigate coupled water and sediment fluxes which could provide insight as to whether systems are sediment supply or transport limited.

Although the precise severity of the risk to each delta's sustainability is unknown due to a paucity of information on the current states of the deltas and the links to fluvial sediment delivery, it is clear that all three deltas are at risk from reduced sediment delivery, whether historical or projected, which has the potential to alter the state of the systems. Changes in the catchment system should be assessed in terms of their effects on the deltas systems, considering whether catchment development can proceed in ways that minimise downstream impacts, for instance by minimising sediment trapping in reservoirs as previously mentioned. This would admittedly be a complex process considering the transboundary nature of the catchments feeding the three deltas, and would be a major innovation in policy. However, it is vital for downstream countries that any upstream catchment changes are discussed with regards to their impact on the deltas, particularly in regards to the key activities of reservoir construction, other channel engineering, and land use such as changing agricultural practices. If catchment development continues without systematic, integrated, catchment wide management it is possible that the delta systems will be (potentially further) destabilised, disrupting the lives and livelihoods of those that live or depend on the deltas.

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