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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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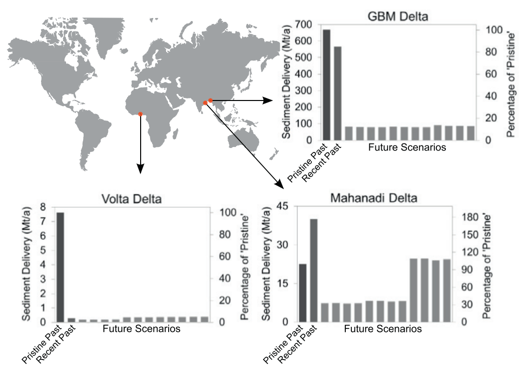
HIGHLIGHTS

- 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