Geomorphology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas

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ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 28 September 2017
Accepted 28 September 2017
Available online xxxx

Keywords:
River deltas
Sea level rise
Environmental change
Coastal geomorphology

ABSTRACT

Modern deltas are dependent on human-mediated freshwater and sediment fluxes. Changes to these fluxes impact delta biogeophysical functioning and affect the long-term sustainability of these landscapes for human and for natural systems. Here we present contemporary estimates of long-term mean sediment balance and relative sea level rise across 46 global deltas. We model scenarios of contemporary and future water resource management schemes and hydropower infrastructure in upstream river basins to explore how changing sediment fluxes impact relative sea level rise in delta systems. Model results show that contemporary sediment fluxes, anthropogenic drivers of land subsidence, and sea level rise result in delta relative sea level rise rates that average 6.8 mm/y. Assessment of impacts of planned and under-construction dams on relative sea level rise rates suggests increases on the order of 1 mm/y in deltas with new upstream construction. Sediment fluxes are estimated to decrease by up to 60% in the Danube and 21% in the Ganges-Brahmaputra-Meghna if all currently planned dams are constructed. Reduced sediment retention on deltas caused by increased river channelization and management has a larger impact, increasing relative sea level rise on average by nearly 2 mm/y. Long-term delta sustainability requires a more complete understanding of how geophysical and anthropogenic change impact delta geomorphology. Local and regional strategies for sustainable delta management that focus on local and regional drivers of change, especially groundwater and hydrocarbon extraction and upstream dam construction, can be highly impactful even in the context of global climate-induced sea level rise.

1. Introduction

Most modern coastal river deltas date from the late Holocene when post-Last Glacial Maximum (LGM) sea level rise rates decreased sufficiently to enable sediment fluxes from upstream river basins to build and maintain more permanent deltaic landforms (Stanley and Warne, 1994). The balance between delivery of new sediment and sea level rise continues to be a major determinant of delta geomorphology (Giosan et al., 2014). How anthropogenic factors influence the interactions and fluxes between deltas, their upstream river basins, and the coastal ocean domains is a key question for understanding how deltas are changing today and into the future. That large populations currently reside on deltas, estimated at ~500 million globally (Tessler et al., 2015; Higgins, 2016), adds urgency to the challenge of forecasting and managing delta geomorphic change.

While global climate change and sea level rise presents challenges for coastal regions around the world (Nicholls and Cazenave, 2010; Hinkel et al., 2014), delta regions present a compound challenge owing to the dual impacts of sea level rise and coastal land subsidence, jointly referred to as relative sea level rise (RSLR). Land subsidence occurs naturally in deltas (e.g., Tornqvist et al., 2008) and can be human-induced by groundwater and hydrocarbon extraction. But in addition, anthropogenic activities can reduce upstream river basin fluxes of water and sediment and can control or prevent natural depositional processes within the delta bounds. Reduced delivery or deposition of sediment results in undercompensation of land subsidence and increased rates of RSLR.

Within deltas, physical characteristics of the sediments in transport are known to be an important factor in how channels and islands evolve. In numerical models, differences in sediment cohesion are capable of driving major changes in delta morphology (Edmonds and Slingerland, 2009; Tejedor et al., 2016), while vegetation height and density influence sediment deposition location, controlling delta slope (Nardin et al., 2016). Graph-theoretical analysis of deltaic river network structure has also been used to assess how vulnerability to fluvial change varies spatially within deltas and how these structures change

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Please cite this article as: Tessler, Z.D., et al., A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas, Geomorphology (2017), https://doi.org/10.1016/j.geomorph.2017.09.040

with delta evolution (Tejedor et al., 2015a, 2015b). Physical and biogeochemical processes within deltaic environments exert strong control on the spatial patterns of sediment deposition and erosion and on the evolution of delta morphology. External processes, such as from upstream anthropogenic activities, affect the boundary conditions that determine sediment and freshwater fluxes entering the delta. This study focuses on how these larger-scale external drivers vary across deltas at the global scale and on the impact they have on delta land elevation stability.

Recent work at the global scale has led to new tools for quantifying and comparing change in deltas (Ericson et al., 2006; Syvitski et al., 2009) and how those changes impact and interact with humans and infrastructure (Day et al., 2016; Tessler et al., 2015). A sustainable future for deltas will depend on our capacity to quantify current rates of RSLR, as impacted by the variety of natural and human-controlled environmental and geomorphic agents of change. Several comparative, global-scale methods have been developed and applied to global distributions of delta systems. Expert assessment methods (Syvitski et al., 2009; Day et al., 2016) can be difficult to validate or use to monitor change over time. Nonphysical heuristic or index-based models (Tessler et al., 2015) typically rely on normalization of a suite of indicator variables. While the normalization methods used by Tessler et al. (2015) improve index robustness, they are only weakly sensitive to change. This results in limited capacity to analyze future geophysical and anthropogenic scenarios or to evaluate potential outcomes from specific delta management strategies.

In this paper, we develop an RSLR model based on sediment mass balance suitable for use at the global scale by extending the delta RSLR model of Ericson et al. (2006) and combining it with the sediment flux model by Syvitski and Milliman (2007). We build a suite of past and contemporary scenarios to estimate current rates of sediment fluxes and RSLR and of future scenarios of dam development, climate, and coastal management to forecast potential future challenges. We highlight where multiple anthropogenic and geophysical stressors are jointly acting on particular deltas and provide estimates of future ranges of RSLR that can be expected from an assessment of individual and joint drivers of change.

2. Methods

Changes in the relative rate of sea level rise of 46 deltas (Fig. 1), selected from those in several other global-scale comparative studies (Ericson et al., 2006; Syvitski et al., 2009; Tessler et al., 2015) over a century time-scale are investigated using several watershed- and delta-scale numerical models. Input data from the literature is used to define contemporary environmental, geophysical, and anthropogenic conditions. These inputs are modified to simulate a suite of past, contemporary, and possible future conditions.

2.1. A model of relative sea level rise

We estimate the rate of relative sea level rise across a global sampling of deltas using a simple surface elevation model based on Ericson et al. (2006). We estimate the aggregate effect of major delta processes averaged over the full spatial extent of each delta. Delta extents were defined using existing maps from the literature, compiled and digitized by Ericson et al. (2006). These were augmented by Tessler et al. (2015) using optical remote sensing to map vegetation patterns and the locations of upstream river bifurcations, as well as the presence of soils of fluvial origin (*FAO*, 1974; Fischer et al., 2008).

While spatial variability of land subsidence in deltas can be substantial even at the kilometer-scale (e.g., Higgins et al., 2013), here we model average RSLR within deltas based on changes to sediment fluxes at the delta apex. These estimates are meant to be indicative of rates of change and sustainability of the delta system as a whole. The surface elevation balance is taken as

$$R = C_N + C_A + I + T + S - A \quad (1)$$

where the relative sea level rise rate R changes over time as a result of sediment compaction rate C, isostatic adjustment rate I, other tectonic motion T, sediment aggradation rate A, and eustatic sea level rise rate S. Sediment compaction is further separated into natural C_N and anthropogenic C_A components. All components are in units of $L\,T^{-1}$. Below, we use the term *subsidence* to refer to $(C_N + C_A + I + T)$, and *natural subsidence* to refer to $(C_N + I + T)$. Any of these components can be spatially heterogeneous even over small scales (Higgins et al., 2013). However, to establish general estimates of vulnerability we estimate the average RSLR conditions within deltas as indicators of rates of change and sustainability of the delta system as a whole, while acknowledging that RSLR can vary substantially at subdelta scales. Similar coarse-scale sediment balance models have been used to investigate delta sustainability given contemporary sediment flux rates for specific deltas, including the Mississippi (e.g., Blum and Roberts, 2009) and the Ganges-Brahmaputra (Darby et al., 2015).

2.2. Model components and input data sets

We estimate the terms in this balance using a series of sub models and input data sets. We implement a range of past, contemporary, and

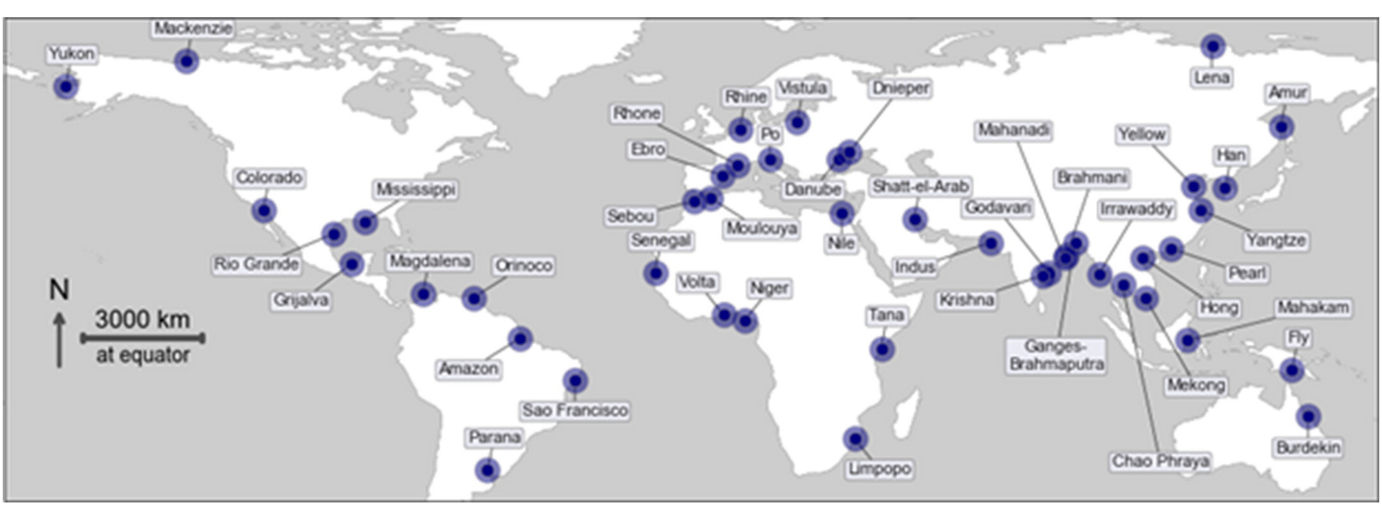

Fig. 1. Locations of deltas included in this study.

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