

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

Zachary D. Tessler^{a,*}, Charles J. Vörösmarty^{a,b}, Irina Overeem^c, James P.M. Syvitski^c

^a Environmental Sciences Initiative, Advanced Science Research Center at the Graduate Center of the City University of New York, New York 10031, USA

^b Department of Civil Engineering, City College of New York, New York 10031, USA

^c CSDMS/INSTAAR, University of Colorado - Boulder, Boulder, CO 80309, USA

ARTICLE INFO

Article history:

Received 15 May 2017

Received in revised form 28 September 2017

Accepted 28 September 2017

Available online 2 October 2017

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.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

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 Varne, 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

* Corresponding author.

E-mail addresses: zachary.tessler@asrc.cuny.edu (Z.D. Tessler), charles.vorosmarty@asrc.cuny.edu (C.J. Vörösmarty), irina.overeem@colorado.edu (I. Overeem), james.syvitski@colorado.edu (J.P.M. Syvitski).

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.

future environmental and anthropogenic scenarios by modifying the input data sets.

2.2.1. Natural subsidence

Delta land surface subsidence occurs naturally in the absence of anthropogenic processes (Tornqvist et al., 2008) through sediment compaction and vertical tectonic movement of the earth's crust. Natural compaction of sediments occurs when porewater is lost from interstitial spaces caused by the weight of overlying sediment or through rearrangement of sediment particles (Brain, 2016). Compaction of peat can be the dominant contributor to overall sediment compaction, particularly in late Holocene deposits that make up some modern deltas (van Asselen, 2011; Tornqvist et al., 2008; van Asselen et al., 2009). In addition to reduction of sediment volume, tectonic processes result in changes to surface elevation (I in Eq. (1)) through uplift or subsidence of the full sediment column. Glacial isostatic adjustment (GIA) since the Last Glacial Maximum is included explicitly in the RSLR model using coarse resolution Gravity Recovery and Climate Experiment (GRACE) satellite-based estimates of GIA vertical uplift rates (A et al., 2013). Natural compaction and non-GIA tectonic motion is estimated implicitly by considering the surface elevation balance absent anthropogenic factors (the *Pristine* scenario, described below).

Assuming a constant sediment supply and constant rate of natural subsidence, contemporary delta extents can be maintained in approximate steady-state under nonanthropogenic conditions. In this idealized scenario, sediment delivery, retention, and aggradation are balanced by natural subsidence and sea level rise. With modeled sediment fluxes and sea level rise rates from the literature, we compute an estimated natural subsidence rate for each delta from Eq. (1). Given that delta initiation occurred around the globe following the Holocene sea level rise deceleration around 8 ka (Stanley and Warne, 1994; Hori and Saito, 2007), this assumed balance cannot hold true over longer timescales. However, it provides a measure of the average subsidence rates during the late Holocene necessary for the maintenance of modern deltas during a period of relatively stable sea level rise rates and external climate forcing (Stanley and Warne, 1994; Wanner et al., 2008). Over this longer 8 ka timescale, assuming constant sediment fluxes would require smaller subsidence rates to allow for sufficient progradation to build modern deltas.

We note that errors in the natural subsidence rate estimated under the preanthropogenic scenario will contribute directly to errors in absolute rates of RSLR computed for other scenarios through the C_N term in Eq. (1). However, since C_N is unaffected by anthropogenic activity, these errors do not affect comparative differences in RSLR between the various contemporary and future scenarios of anthropogenic impact. The timescales on which anthropogenically driven subsidence and sea level rise rates change are shorter than those for natural subsidence rates, which we hold constant between each scenario, and in all future outlooks (to 2100). While absolute RSLR estimates are useful to provide coastal risk context for each scenario, we expect the estimate of natural subsidence to be a primary source of error in RSLR values. Our analysis therefore focuses on differences in RSLR between scenarios as a result of anthropogenic activity, where errors in estimated natural subsidence rates have no effect.

2.2.2. Anthropogenic sediment compaction

Sediment compaction is enhanced by active anthropogenic extraction of fluids from within deltaic sediments that are of value to society, in particular groundwater and hydrocarbons. We estimate a snapshot of the magnitude of these processes in global deltas following Ericson et al. (2006). Net groundwater abstraction rates, compensated for groundwater recharge, for each delta are extracted from a global groundwater model (Wada et al., 2012; Wada and Bierkens, 2014) consisting of country-level estimates of groundwater extraction that were spatially downscaled using local water demand and recharges rates from a hydrological model. Note that illegal or unregistered water withdrawals

are not reported in these data sources, which can be substantial in some places (Chaussard et al., 2013; Holzer and Johnson, 1985), and may result in underestimation of sediment compaction in this model. Water table drawdown rates are estimated from net groundwater abstraction rates and delta area assuming a specific yield of 20% for typical deltaic sediments (Fetter, 2001). Resulting anthropogenic subsidence rates as a result of groundwater removal are computed as a multiple of each delta's natural rate of subsidence. The delta with the largest absolute drawdown rate is assigned a natural subsidence multiplier value of three (Milliman, 1997), with other delta multipliers reduced proportionally by drawdown. In practice, we find groundwater abstraction to be a significant factor for contemporary deltas primarily in arid regions, including the Rio Grande, Colorado, Godavari, Indus, Shatt-el-Arab, and Nile deltas. Large urban areas often experience rapid groundwater extraction and associated subsidence, with Bangkok on the Chao Phraya delta being one notable example (Phien-wej et al., 2006). Note that groundwater extraction has also been observed to be important on smaller spatial scales than those considered here: in the Yellow River delta and others where aquaculture is becoming an increasingly important economic activity (Higgins et al., 2013).

Hydrocarbon extraction is an additional anthropogenic contributor to sediment compaction. While country-level data documenting oil and gas production is available from national and international sources, spatially disaggregated data suitable for estimating production volumes from delta sediments is not available at the global scale. The most recent USGS maps of oil- and gas-producing regions are used to identify deltas with recent or ongoing hydrocarbon extraction (USGS World Energy Assessment Team, 2000). Subsidence rates in deltas showing evidence of groundwater extraction or hydrocarbon production were incremented by 1 mm/y (Ericson et al., 2006).

2.2.3. Sediment flux and aggradation

Sediment aggradation A is estimated by a delta-scale mass balance, where some fraction r of the sediment flux Q_s from the upstream contributing basin is retained and distributed over the delta area a :

$$A = \frac{Q_s * r}{\rho * (1 - \phi) * a} \quad (2)$$

using a sediment density of $\rho = 1.5 \text{ g/cm}^3$ and a water-filled porosity ϕ of 45%. We model sediment flux at the delta apex using the BQART model (Syvitski and Milliman, 2007), an empirical model of average fluvial sediment flux based on river discharge; basin area, relief, and temperature; erosion factors including glacier coverage and basin lithology; and anthropogenic factors including artificial reservoirs and proxies for agricultural practices (Table 1). This model is based on an empirical fit to sediment flux measurements and river basin properties across 294 rivers worldwide and validated against an additional 194 rivers. Intra- and interannual sediment flux variability is not captured by this model; resulting sediment aggradation and RSLR estimates likewise do not reflect this variability.

Table 1
Input data to the BQART model.

Variable	Data source
River discharge	WBMplus hydrological model (Wisser et al., 2010a, 2010b; Haddeland et al., 2014)
Basin area	STN-06, HydroSHEDS (Fekete et al., 2001; Lehner et al., 2008)
Basin relief	ETOPO1 (Amante and Eakins, 2009; Cohen et al., 2013)
Air temperature	NCEP Reanalysis, 1948–2010 mean (Kalnay et al., 1996)
Lithology	Dürr et al., 2005; Syvitski and Milliman, 2007
Ice cover	ICE-5G (Peltier, 2004)
Per capita GDP	The World Bank - World Development Indicators 2016
Population	GPWv4 (Center for International Earth Science Information Network, 2016)
Artificial reservoirs	GRanD v1.1 (Lehner et al., 2011), Zarfl et al., 2015

2.2.4. River discharge

Mean river discharge is a key input to the *BQART* sediment flux model. The global hydrological model *WBMplus* provides contemporary and future river discharge under a range of climate forcings (Wisser et al., 2010a, 2010b; Cohen et al., 2013; Haddeland et al., 2014). The *WBMplus* is a cell-based water balance model with land cover, irrigation, and artificial reservoir modules and is forced by historical climate analysis data from the Global Precipitation Climatology Project (GPCP; Adler et al., 2003) and CMIP5 bias-corrected future precipitation from the GFDL-ESM2M model (Dunne et al., 2012; Davie et al., 2013; Hempel et al., 2013). Runoff in each grid cell is routed along the *STN-06 Simulated Topological Network*, a digital river flowline database at 6-arc min resolution, based on the near-global, high-resolution *HydroSHEDS* river network (Fekete et al., 2001; Lehner et al., 2008) and routed to the apex of each delta in the study.

2.2.5. Artificial reservoir sediment trapping

Dams and artificial reservoirs provide services to regional and downstream communities: power generation, irrigation or drinking water supply, or flood control. Water impounded in reservoirs, by definition, moves more slowly than elsewhere in the river network; and the lower energy flow allows settling of suspended sediment to the reservoir bottom. We estimate the reduction in sediment flux for a given river basin as a result of reservoir trapping following Vörösmarty et al. (2003), relating sediment trapping efficiency of artificial reservoirs to the increase in water residence time. Vörösmarty et al. (2003) computed the sediment reduction of a full basin as the discharge-weighted average of the trapping efficiency of individual dam-regulated subbasins. Subbasins are defined as the portion of a river network upstream of an impoundment. The trapping efficiency of each subbasin i is

$$TE_i = 1 - \frac{0.05}{\sqrt{\Delta t_i}} \quad (3)$$

where the change in residence time for a given sub-basin, Δt_i , is

$$\Delta t_i = \frac{\sum V_j}{Q_i} \quad (4)$$

Here V_j represents the volume of each reservoir within a subbasin, and Q_i is the subbasin discharge. Trapping efficiency for the full basin TE is computed as the discharge-weighted average of trapping efficiency within each subbasin,

$$TE = \frac{\sum TE_i Q_i}{Q} \quad (5)$$

where Q is the discharge at the river mouth (or delta apex). This sediment trapping model reflects the geographic distribution of reservoirs and water resources within the basin. We note that this model does not include the effects of small ponds that can impound substantial volumes of sediment in aggregate (Renwick et al., 2005). While the

geographic locations of existing (large) reservoirs are known, potential future reservoirs must be assigned locations on the river network. We describe our method for determining reasonable reservoir sites below.

2.3. Scenarios

We have implemented several versions of the RSLR model (Eq. 1) by varying input data to estimate rates of RSLR under different forcing scenarios. We employed four main contrasting scenarios of the future, and a further three minor modifications to the baseline scenario (Table 2). The *contemporary* scenario (S_{con}) represents our baseline and uses input data that best matches modern delta systems, including human and geophysical factors. This scenario uses a global mean sea level rise rate of 3.2 mm/y (Church and White, 2011; Rhein et al., 2013). The modern-day scenario also includes sediment trapping impacts from dams and reservoirs, enhanced erosion caused by modern land use practices in the basin, and takes into account groundwater and hydrocarbon extraction in the deltas. Other scenarios are developed primarily by modifying S_{con} and documenting the resulting relation to the present-day condition. The *pristine* scenario (S_{pri}) uses modern estimates of geophysical processes but with all anthropogenic influences removed. This scenario thus includes none of the following: artificial dams and reservoirs, anthropogenically enhanced upland erosion, groundwater or hydrocarbon extraction. It assumes a global mean sea level rise rate of 0.2 mm/y, derived from the IPCC's assessment of late Holocene sea level rise rates (Church et al., 2013).

We developed two additional scenarios to simulate snapshots of potential expansion of dams and artificial reservoir construction. The first, *planned reservoir growth* (S_{rplan}), is based on a database of dams and reservoirs for hydropower projects > 1 MW that were either in a late planning phase or under construction between August 2012 and February 2014, developed by Zarfl et al. (2015). This data complements the GRanD dam database (Lehner et al., 2011), which contains 6862 georeferenced records of artificial reservoirs with storage capacity > 0.1 km³, published in 2011 but based in large part on the World Register of Dams database, which contains > 55,000 records up to 2009 (International Commission on Large Dams [ICOLD], 2009). Both data sets are conservative in that they focus only on the largest projects, and large projects constructed between 2009 and August 2012 may be missed.

The second future reservoir scenario, *potential reservoir growth* (S_{rpot}), is based on potential future development of hydropower resources given geographical and hydrological resource constraints. Potential hydropower energy PE_i originating from water runoff in a given *STN-06* grid cell i is proportional to the product of runoff R_i and elevation Z_i assuming that all runoff eventually reaches sea level. Over all grid cells within an entire river basin, the total hydropower potential energy PE scales with

$$PE \propto \sum_i R_i Z_i \quad (6)$$

This sum does not consider losses from evapotranspiration and deep groundwater recharge, both of which reduce the potential hydraulic

Table 2

Key scenario parameters (italicized parameters denote difference from the baseline contemporary scenario).

Scenario	Sea level rise rate, 2000 (mm/y)	Sea level rise rate, 2100 (mm/y)	Dams and reservoirs	Delta sediment retention fraction
Contemporary (S_{con})	3.2	3.2	GRanD	0.3
Pristine (S_{pri})	0.2	0.2	None	0.3
Planned reservoir growth (S_{rplan})	3.2	3.2	GRanD + planned/under-construction	0.3
Potential reservoir growth (S_{rpot})	3.2	3.2	Additional reservoirs to match current Mississippi River Basin utilization	0.3
RCP 2.6 ($S_{2.6}$)	3.2	4.4	GRanD	0.3
RCP 8.5 ($S_{8.5}$)	3.2	11.2	GRanD	0.3
Low sediment retention (S_{low})	3.2	3.2	GRanD	0.1

head as some runoff does not reach sea level. This resource is quantified here in terms of potential energy, the relevant quantifier for hydropower placement. An estimate of potential irrigation resource could also be constructed in a similar way to assess dam placement for flow control, though evapotranspiration losses can be particularly substantial for irrigation use cases. We also estimate contemporary total artificial reservoir volume V , from all reservoirs in the GRanD database within a given basin. Then, hydropower resource utilization U is calculated as $U = V/E$. Utilization normalizes the current reservoir volume across tributaries and the mainstem of a river basin by that basin's hydropower potential. We construct the *potential reservoir growth* scenario by placing additional reservoirs in each river basin in order to make its aggregate utilization value equal to that of the Mississippi River basin. We choose the Mississippi as an example of a basin where hydropower resources are nearly fully utilized – in many cases the U.S. is decommissioning dams because ongoing maintenance and environmental costs exceeding their useful value (Pohl, 2002; Doyle et al., 2003; Pacca, 2007). Potential future reservoirs in S_{rpot} are geospatially placed on the river network with respect to PE . Hydropower dams access energy from the upstream river network. We route and aggregate PE a limited distance downstream (3 nodes) and place reservoirs at locations to maximize aggregate PE . The downstream routing distance is a heuristic measure designed to keep placed reservoirs in regions of high runoff and relief. Increasing the routing distance has the effect of shifting placed reservoirs downstream, ultimately to the river mouth, and increasing the basinwide sediment trapping efficiency. In cases where basins have current hydropower utilization rates greater than that of the Mississippi, often geographically small and highly developed basins, we proportionally reduce the size of all existing reservoirs to reflect future decommissioning.

We further modify the contemporary S_{con} scenario to represent two possible future sea level rise trajectories based on IPCC estimates of sea level rise rates under RCP 2.6 and 8.5 (Church et al., 2013). Scenario $S_{2.6}$ sea level rise rate changes linearly from 3.2 mm/y in 2000 to 4.4 mm/y in 2100, while $S_{8.5}$ changes to 11.2 mm/y in 2100. These scenarios are otherwise the same as S_{con} .

Finally, we explore the RSLR rate sensitivity to differences in delta sediment retention, a key parameter that controls the fraction of sediment entering the delta via the upland river network that is then retained on the subaerial delta. Modern delta flood protection infrastructure and river channelization reduces sediment retention rates by preventing inundation of delta floodplains (Syvitski et al., 2005, 2009) and thus shunts sediment offshore into coastal waters. While the S_{con} scenario uses a retention rate of 0.3 for all deltas, the *low sediment retention* scenario (S_{low}) decreases this to 0.1 (Blum and Roberts, 2009; Goodbred and Kuehl, 1998).

3. Results

3.1. Natural subsidence rates

Estimated rates of natural subsidence necessary for delta maintenance, taking account of sediment compaction, glacial isostatic adjustment, and other tectonic factors, vary from a high of 44.6 mm/y in the Paraná delta to -0.3 (uplift) in the Han delta, with a mean of 5.2 mm/y across all deltas in the study (Fig. 2). While these long-term averages assume a stable delta, neither prograding nor retrograding, this assumption is not expected to hold true over specific short-term time periods, including contemporary timeframes. The rates estimated from this model are therefore most useful to provide a scale for evaluating how changes in sediment fluxes or anthropogenic compaction rates translate to relative sea level rise. Nevertheless, the rates that are computed here are reasonable for most deltas in the study with respect to reported values of natural subsidence. Our estimate of 7.8 mm/y natural subsidence in the Mississippi, for instance, falls within the reported range of 1–9 mm/y, the majority of which is likely from compaction of

Holocene sediments (Meckel, 2008; Tornqvist et al., 2008; Blum and Roberts, 2009).

A dominant factor in the estimated natural subsidence rates is the ratio of sediment flux under pristine conditions to delta area. The Sebou and Moulouya deltas, with natural subsidence rates of 0.006 and -0.07 mm/y respectively, have several orders of magnitude lower sediment flux per unit area of subaerial delta (0.002 and $0.003 \text{ kg s}^{-1} \text{ km}^{-2}$) than the Paraná ($3.9 \text{ kg s}^{-1} \text{ km}^{-1}$). We note that computed subsidence rates in deltas with very small areas will be more sensitive to errors in mapping the delta extent.

3.2. Fluvial sediment fluxes

Anthropogenic impacts on sediment fluxes to deltas are a key driver of contemporary and future RSLR rates. Here we examine how these fluxes vary across different scenarios of anthropogenic change. The resulting RSLR rates are presented below. In comparison to pristine nonanthropogenic conditions, the contemporary scenario considers sediment trapping behind existing dams and artificial reservoirs (Vörösmarty et al., 2003; Syvitski and Milliman, 2007), as well as enhanced soil erosion from agriculture. For each delta, we sum all STN-06 digital river fluxes that discharge within the geographic bounds of the river delta. In most cases, the freshwater and sediment fluxes are dominated by a single large basin. However, there are important exceptions, such as the Ganges-Brahmaputra-Meghna delta that is formed from the confluence of three major rivers that together drain portions of India, China, Nepal, Bangladesh, and Bhutan.

Under contemporary conditions, we find nearly all deltas receive substantially reduced sediment fluxes from upstream compared to pristine conditions (Fig. 3). The average percent change in sediment flux between pristine and contemporary conditions across all deltas in the study is 36%, with the median delta receiving 39% less sediment. Deltas with few upstream dams, including the Amazon, Magdalena, Orinoco, and Fly are still receiving most of their preindustrialization sediment fluxes. Our model shows several deltas receive increased sediment fluxes in comparison to pristine conditions, including the Godavari, Krishna, Mahanadi, and Brahmani, all in India. The sediment flux increase derives from the anthropogenic factor E_h in the BQART model (Syvitski and Milliman, 2007). This factor accounts for anthropogenic processes worldwide that contribute to soil conservation or erosion, such as deforestation, agricultural practices, and mining. As a general trend, in drainage basins with high population density and relatively low per capita GNP, E_h is set > 1 , indicating that erosive processes dominate and sediment fluxes increase relative to preanthropogenic conditions. It remains debatable whether the E_h approach is appropriate for basins, such as those in India, with extensive rice farming, which can sustain dense populations but as a land management practice may be efficient in retaining sediment (Rao et al., 2015).

Though many industrialized nations are decommissioning old dams as their maintenance and environmental costs exceed their value, dam construction is continuing in many less-developed river basins worldwide (Kuenzer et al., 2012; Zarfl et al., 2015; Winemiller et al., 2016). Results from the S_{rplan} (*planned reservoir growth*) scenario show potential for further decreases in sediment fluxes from the 14 major river basins where data was available (Table 3). Planned dam construction is found to be particularly impactful in the Danube, Indus, and Senegal deltas, where reductions in sediment flux of 60%, 59%, and 52% are estimated respectively. The basins above the five largest deltas by area in this study are all sites of planned dam expansion: the Amazon (Finer and Jenkins, 2012; Winemiller et al., 2016), Ganges (Baten and Titumir, 2016; Grumbine and Pandit, 2013), Mekong (Grumbine and Xu, 2011; Kuenzer et al., 2012), Yangtze (Yao et al., 2006), and Irrawaddy (Brakenridge et al., 2016). We estimate that these systems face sediment flux decreases of 2% (Amazon), 21% (Ganges), 11% (Mekong), 35% (Yangtze), and 12% (Irrawaddy) if all planned dams are constructed. These reductions are on top of sediment flux losses from existing

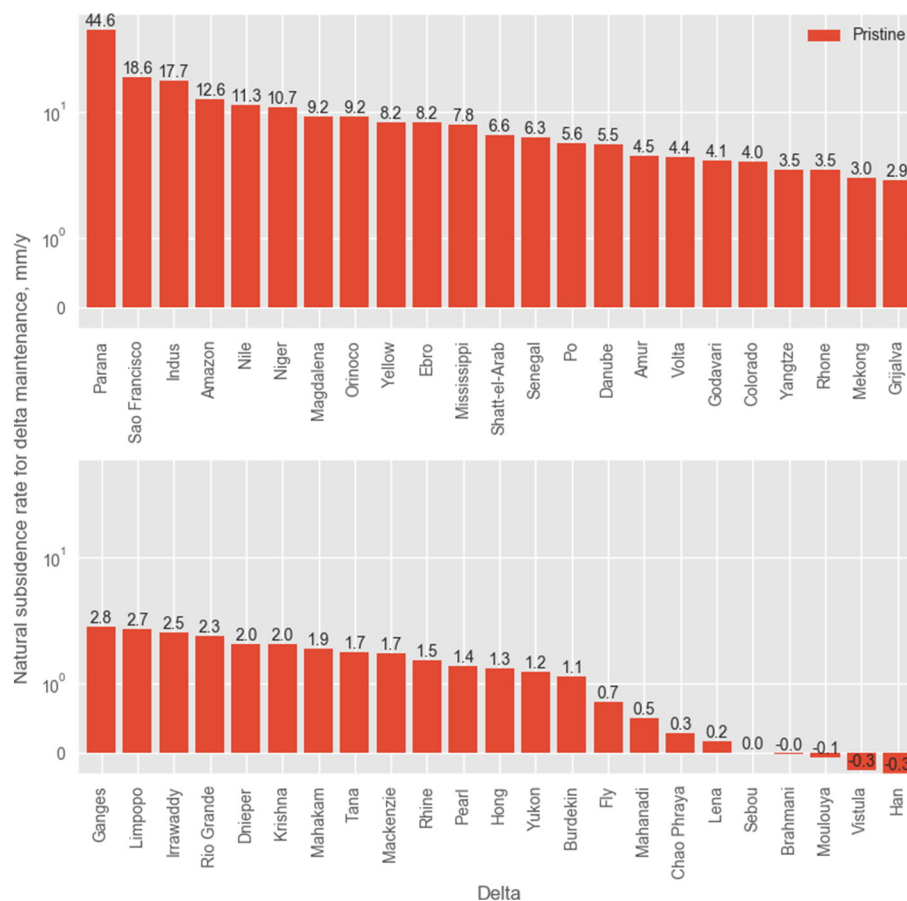


Fig. 2. Estimated natural subsidence rates necessary for delta maintenance given constant sediment flux, sediment deposition, and sea level rise rate under pristine, nonanthropogenic conditions. Note scale is logarithmic above 1 mm/y, linear below.

dams. Under the S_{pot} , sediment fluxes in the same five large deltas decrease by 5%, 27%, 11%, 34%, and 19% relative to S_{con} , comparable to reductions in S_{plan} . Planned dams in the Danube, Senegal, and Nile would bring their upstream basin hydropower resource utilization rates substantially higher than the current Mississippi River basin utilization rate.

3.3. Relative sea level rise

Rates of RSLR under the S_{con} range from a high of 25.0 mm/y in the Indus River delta to a low of 2.5 mm/y in the Krishna River delta, with a mean rate of 6.8 mm/y (Fig. 4). The RSLR rates in S_{pri} are zero for all deltas, by definition. For comparison, estimates of RSLR derived from tide gauge record comparisons between gauges on the respective deltas and nearby stable coastal stations supplemented by ranges in the literature, as collected by Syvitski et al. (2009) are included in Fig. 4. The S_{con} RSLR rate estimates are reasonably consistent with the range of estimates from the literature for most deltas, where available. High and low estimates from stratigraphy, tide gauge, GPS, and InSAR studies can be sensitive to spatial and temporal variability within individual deltas that is not accounted for in the model here. Higgins et al. (2013) for instance found local subsidence rates as high as 250 mm/y in the Yellow River delta in small areas (approximately several kilometers) caused by groundwater extraction for aquaculture. Our methodology accounts for these withdrawals in the aggregate and distributes the effect of groundwater extraction over the full delta.

The difference between sediment flux in the S_{pri} and S_{con} scenarios is a key driver for high S_{con} RSLR estimates. The Indus delta RSLR estimates are high owing to a large pristine sediment flux relative to the

delta area, with a correspondingly high natural subsidence rate of 17.8 mm/y, and a large reduction in sediment flux, 58%, between S_{pri} and S_{con} scenarios as a result of sediment trapping behind reservoirs and reduced freshwater fluxes. As a result of the large pristine sediment flux relative to the Indus's area, the sediment reduction from artificial reservoir trapping in the upstream basin results in much higher RSLR rate than we see in other deltas experiencing similarly high trapping efficiencies, such as the Mississippi.

The S_{con} scenario applies a global mean sea level rise rate of 3.2 mm/y to all coastlines. Deltas with total RSLR rates not much higher than this are dominated by eustatic SLR, with only a small contribution from land subsidence. Deltas in this category include a range of anthropogenic impact: the highly developed Chao Phraya and Pearl, the moderately developed Magdalena, and deltas with little local or upstream development such as the Amazon, Yukon, and Lena (Tessler et al., 2016). Deltas with moderate rates of RSLR, between 5 and 10 mm/y, include the Danube, Po, Rhine, and Mississippi. The Indus, Nile, and Yellow, among others, have RSLR rates > 10 mm/y in the modeled S_{con} scenario.

Future construction of artificial reservoirs is expected to further reduce sediment fluxes (Table 3), with resulting increases in RSLR rates above current conditions. The Magdalena delta has the greatest difference in RSLR between S_{con} and S_{pot} scenarios, with a 50% reduction in sediment flux leading to an increase in RSLR rates from 3.3 to 7.8 mm/y. Also of note are RSLR increases in the Orinoco (4.5 to 6.0 mm/y) and the Indus (25.0 to 29.7 mm/y). These deltas have upstream basins with relatively underutilized hydropower resources, suggesting potential for future dam and reservoir expansion. The utilization rates in several upstream basins currently exceed the Mississippi,

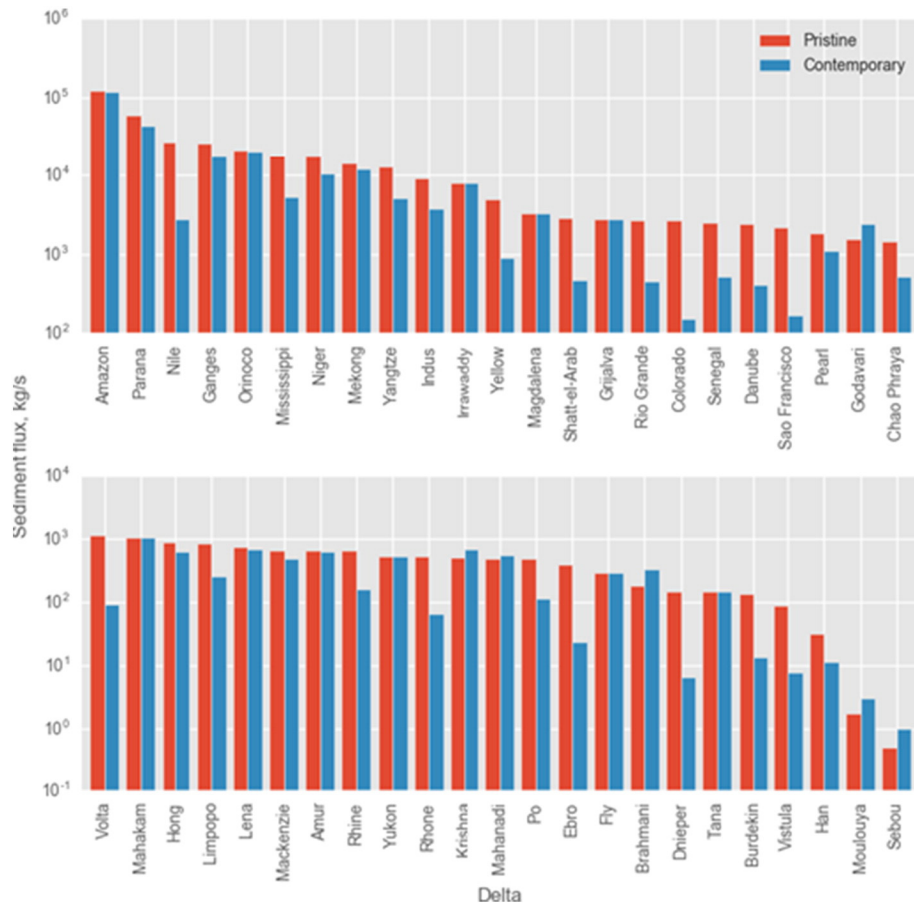


Fig. 3. Sediment fluxes in the pristine (red) and contemporary (blue) anthropogenic forcing scenarios. Note logarithmic scale.

including the Krishna, Volta, Dnieper, and Godavari; and the RSLR in these deltas is lower in S_{spot} than S_{con} . Overall, the mean RSLR rate increases from 6.8 mm/y in S_{con} to 7.2 mm/y in S_{spot} . We note that the S_{spot} scenario does not represent an upper limit on RSLR impacts of

Table 3

Percent decrease in potential sediment flux from contemporary conditions to the planned reservoir growth scenario based on current or planned future dam construction, and the potential reservoir growth based on the Mississippi River basin's current resource utilization rate.

Delta	Percent decrease in sediment flux from contemporary	
	Planned reservoir growth	Potential reservoir growth
Amazon	2%	5%
Amur	5%	5%
Danube	60%	32%
Ganges	21%	27%
Hong	3%	2%
Indus	59%	61%
Irrawaddy	12%	19%
Magdalena	26%	50%
Mekong	11%	11%
Niger	7%	12%
Nile	20%	1%
Senegal	52%	28%
Shatt-el-Arab	3%	– 27% ^a
Yangtze	35%	34%

^a The negative Shatt-el-Arab percent change indicates contemporary utilization is substantially higher than the Mississippi River basin rate, primarily because of the arid climate and low runoff. Changing to match the Mississippi River basin rate would entail reducing reservoir volume compared to contemporary conditions.

dam and reservoir construction. It is possible, even likely, that some river basin utilization rates will exceed that of the modern Mississippi River basin. Currently planned construction in the Danube, Senegal, and Nile (see Table 3) will exceed this estimate if fully developed.

These scenarios have all assumed that half of the sediment delivered to the delta apex is retained on the subaerial delta. The contribution of biogenic sediment, which would not be accounted for in sediment fluxes from the upstream basin, is incorporated into the retention factor. Sediment retention is poorly constrained, with ranges in the literature from ~30–70% (Goodbred and Kuehl, 1998; Blum and Roberts, 2009). Inaccuracies in this factor affect how large of an impact changing sediment fluxes will have on RSLR rates. We also use the low sediment retention (S_{low}) scenario to simulate the impact of delta flood protection and river channelization on the sediment balance. Reduced retention of sediments impacts all deltas, with increases in RSLR over the S_{con} scenario ranging from 0.02 (Vistula) to 21.7 (Paraná) mm/y (Fig. 5). The Paraná is particularly sensitive to the sediment retention rate because of its relatively high sediment fluxes, which in our RSLR model results in high natural subsidence rates. In S_{con} , this is offset by high sediment aggradation rates, though when aggradation is reduced through river channelization the RSLR rates quickly rise. The mean RSLR across all deltas in S_{low} increases by 1.9 mm/y over S_{con} . Combined, the effects of increased reservoir development and reduced sediment retention result in mean RSLR rates increasing from 6.8 to 8.8 mm/y. The impact of the combined scenario over S_{con} RSLR rates is small in most deltas: 39 of 47 deltas have RSLR increases between these scenarios of <2 mm/y. The RSLR rates in the Paraná, Amazon, and Magdalena, however, increase by 21.7, 8.4, and 7.6 mm/y respectively.

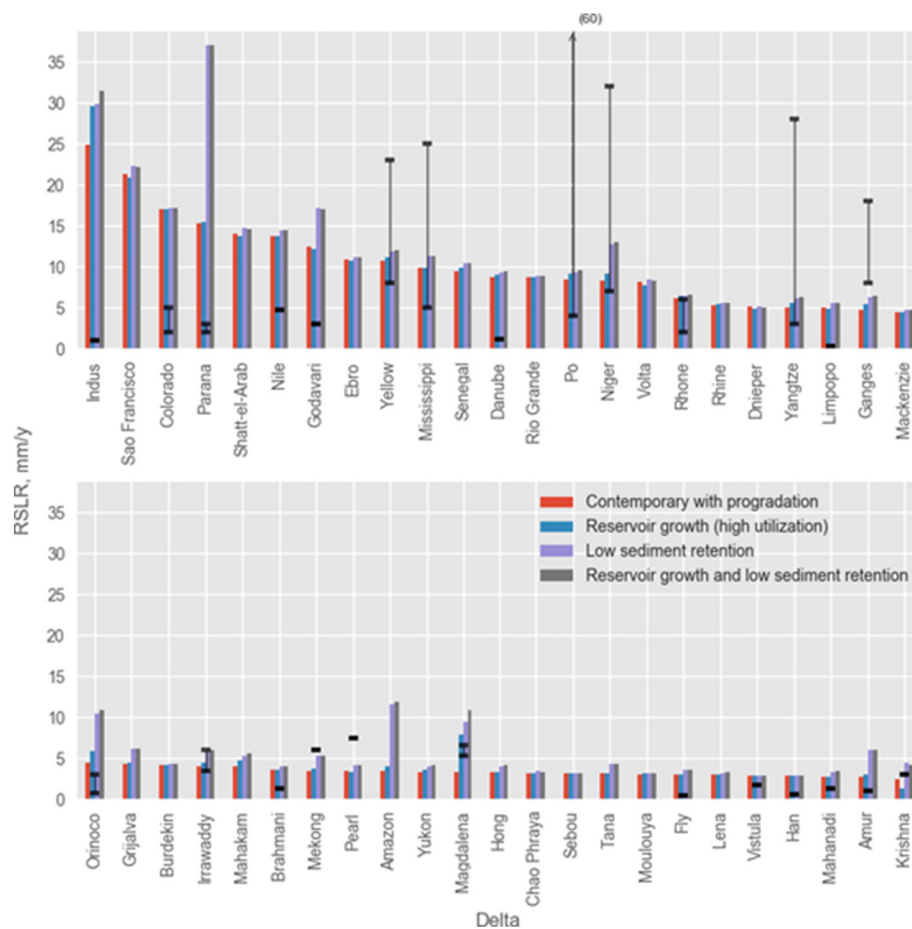


Fig. 4. Comparison of modeled RSLR rates for the *contemporary*, *potential reservoir growth*, and *low sediment retention* scenarios across all deltas. Black lines indicate RSLR ranges in the literature, from Syvitski et al. (2009). Note that the literature estimates are sensitive to spatial and temporal variability that is not captured in the model.

4. Discussion

The sediment flux and RSLR estimate presented in this study provide baselines for average conditions over decadal timescales. Sediment

fluxes vary on much shorter timescales owing to stochastic weather events and interannual variability. These sources of variability can be modeled using different schemes and analyzed in conjunction with the longer-timescale estimates here (Morehead et al., 2003;

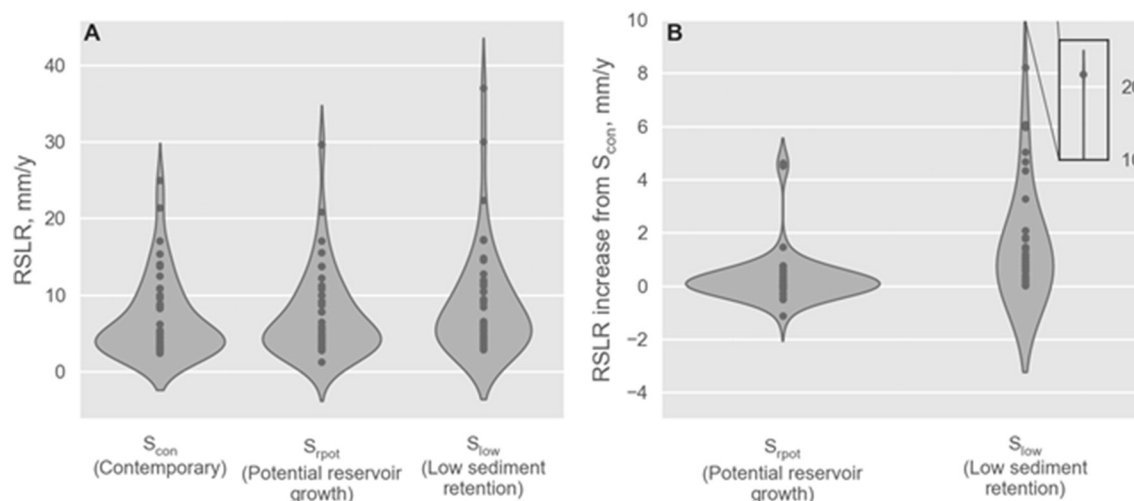


Fig. 5. RSLR rate distributions across three scenarios: S_{con} , S_{pot} , and S_{low} . Widths of the fit distributions are proportional to the number of deltas at a given RSLR rate level. (A) Comparison of RSLR rates for the three scenarios. Most deltas have modeled RSLR rates < 10 mm/y, with several much higher outliers. (B) Increases in RSLR rate over the baseline contemporary scenario, S_{con} . Reservoir growth impacts RSLR in most deltas on the order of 1 mm/y. Reduced sediment retention has a larger impact, increasing RSLR rates up to 2 mm/y and substantially higher for several deltas. Note reduction in vertical scale of inset.

Kettner et al., 2010; Cohen et al., 2013). The spatial and temporal scale of RSLR estimates provided by our model preclude making specific forecasts of future conditions — much of the impact of RSLR on deltas and coastal communities will likely be dominated by local variability that increases coastal risk in specific locations. Nonetheless, we are able to extend current conditions into the future and consider how long-term trends of RSLR are likely to change under different future scenarios. These projections are primarily useful as indicators of potential future conditions given current conditions and rates of change.

The *contemporary* and *potential reservoir growth* scenarios described above focus on impacts of water infrastructure on land subsidence and use a constant rate of sea level rise (3.2 mm/y). However, global mean sea level rise rates are expected to continue to increase over the next century because of accelerated thermal expansion of seawater and melting of Antarctic and Greenland ice sheets (Church et al., 2013). We use RCP 2.6 and RCP 8.5 climate change scenarios to bracket potential sea level rise and to estimate how relative land elevation in several deltas change over the twenty-first century (Fig. 6). Under the RCP 2.6

scenario, rates of sea level rise linearly increase from 3.2 to 4.4 mm/y in 2100, and under RCP 8.5 the rate linearly increases to 11.2 mm/y over the same time period. In most of the deltas in this study, including the Amazon, Mekong, and Ganges shown in Fig. 6, the RSLR impact of the higher RCP scenario is more consequential over time than introducing additional reservoirs, primarily caused by the accelerating nature of the RCP sea level rise trajectories. However, in the Indus and Magdalena deltas, upstream reservoir growth has approximately the same impact on RSLR rates as does transitioning from RCP 2.6 to 8.5. These results highlight how sea level rise projections on their own are insufficient for understanding how delta coastlines are likely to change over the next century. A more complete picture of future delta risk and vulnerability requires integrated assessments of upstream, coastal, and oceanic change.

There are several important sources of uncertainty and potential errors in this model. We have reduced the two-dimensional geography of the delta land surface to one-dimensional for model simplification. Our estimated fluxes and RSLR rates are for areal averages, though in reality

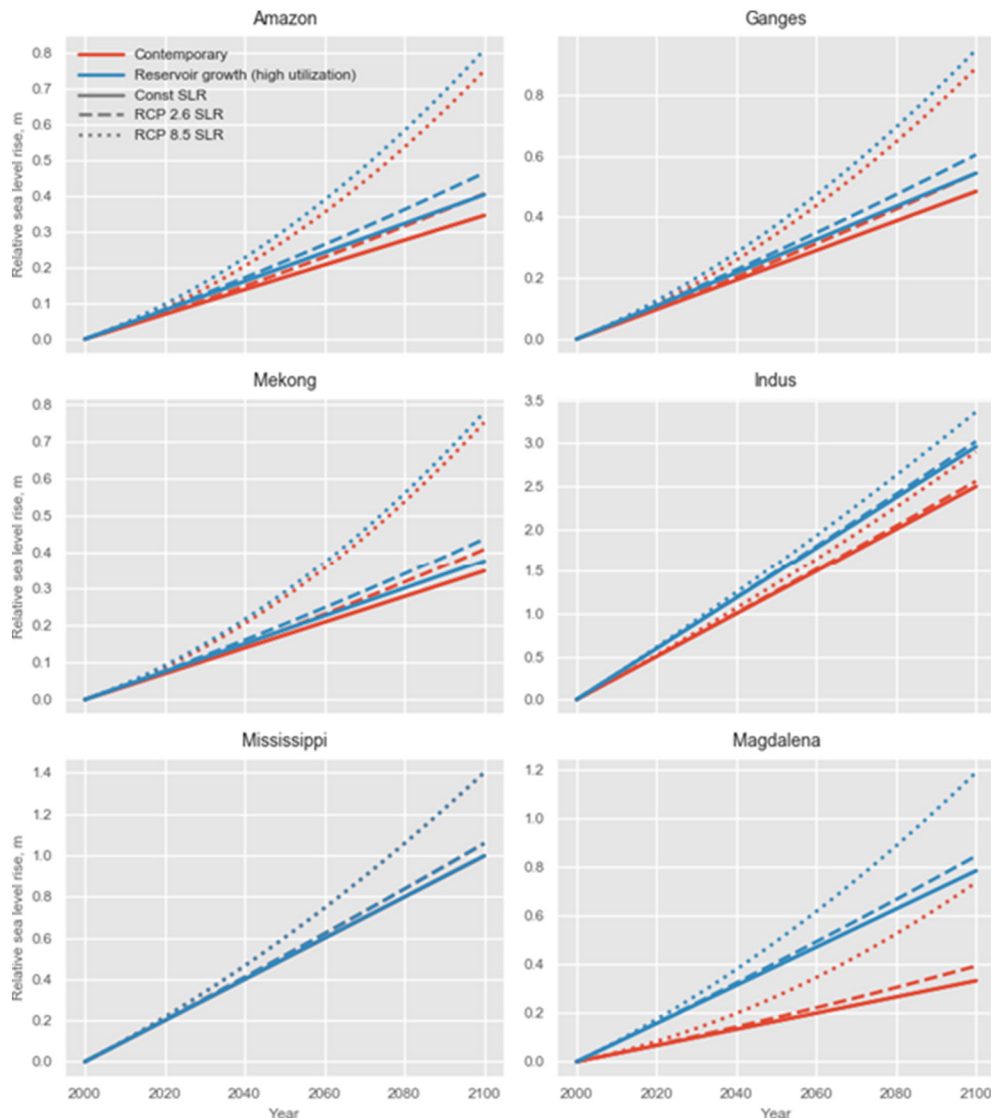


Fig. 6. Cumulative RSLR between 2000 and 2100 for select deltas. Red lines indicate *contemporary* scenarios, blue lines indicate *potential reservoir growth* scenarios with hydropower resource utilization for each basin matched to current Mississippi River basin utilization rates. Solid lines use a constant sea level rise rate of 3.2 mm/y over the full period. Dashed and dotted lines apply a linear increase to estimated 2100 sea level rise rates for the RCP 2.6 and RCP 8.5 climate scenarios. Note that the *potential reservoir growth* scenario is based on the contemporary reservoir distribution in the Mississippi River basin, so this scenario has no effect in the Mississippi River delta.

there will be areas of each delta with much greater subsidence, balanced by areas with less subsidence (e.g., [Wilson and Goodbred, 2015](#)). Existing spatially explicit models of delta morphology highlight the roles of external sediment and oceanic forcing ([Liang et al., 2016a](#)), sediment characteristics ([Edmonds and Slingerland, 2009](#); [Tejedor et al., 2016](#)), and ecosystem structure and function ([Nardin et al., 2016](#)) in determining the evolution of delta structures. For instance, [Liang et al. \(2016b\)](#) find a transition in channel-switching behavior in DeltaRCM, an idealized two-dimensional delta model, when subsidence rates exceed 30 mm/y. These and other smaller-scale dynamics are not captured in our model, though we are able to estimate how changing boundary conditions upstream and offshore of the delta may impact conditions within the delta. Further work is needed to better understand how idealized numerical model findings compare with delta observations, particularly under anthropogenic forcing and management. Coupling boundary-forcing based models (such as the one described in this paper) with process-based delta-scale models presents another possible way forward.

Accuracy of natural subsidence and resulting relative sea level rise estimates are strongly dependent on sediment fluxes. The BQART model used here is a nonlinear, empirical model based on observed mean sediment fluxes and basin-averaged physical, hydrological, climatological, and social characteristics ([Syvitski and Milliman, 2007](#)). Utilization of basin averages suggests that the model performance should improve in larger basins that are less sensitive to small-scale variability in basin characteristics. Indeed, BQART has been found to perform well in large catchments (>10,000 km²), such as the contributing basins upstream of the deltas in this study ([Vente et al., 2013](#)).

We note that our estimation of natural subsidence rates assumes sufficient subsidence to balance sediment aggradation. Deviations from this balance in real systems result in delta progradation or retrogradation. By precluding this possibility, any imbalance appears in the model as an erroneously large or small natural subsidence rate. The very high natural subsidence estimate for the Paraná delta is likely a result of contemporary mean BQART sediment fluxes exceeding the true long-term average in the period since post-LGM sea level rise rates stabilized. If contemporary sediment fluxes are in fact higher than post-LGM averages, then natural subsidence is likely to be more moderate than found in this study. Additionally, this would suggest delta front progradation, as is indeed observed in cartographic, satellite, and modeling studies ([Badano et al., 2012](#)). Reduced natural subsidence rates would also directly reduce our estimated RSLR rates. Similar errors, of either sign, are expected in other deltas, though errors in the Paraná would be proportionally larger than others given its small geographic area. Detailed observations of contemporaneous sediment fluxes, progradation rates, and sediment retention in each delta would be valuable to better constrain estimates of natural subsidence.

5. Conclusions

Low rates of land subsidence and sea level rise are key to long-term sustainability of coastal deltas. These findings highlight the importance of the larger basin-delta-ocean system in controlling the processes that drive delta land elevation change. Construction of new dams and reservoirs is estimated to contribute on the order of an additional 1 mm/y of RSLR, with some deltas potentially exposed to higher RSLR. We also find that reduced sediment retention resulting from coastal infrastructure can further increase RSLR on the order of 2 mm/y. Sea level rise projections on their own are insufficient for projecting future risks and vulnerability in deltas. It is critical for long-term delta sustainability to more fully understand how anthropogenic factors are changing, the underlying social and environmental drivers of those factors, and what impacts those factors will have on delta functions and the delta system as a whole.

Acknowledgements

The authors thank two anonymous reviewers, Guest Editor Dr. David Butler, and Editor-in-Chief Dr. Richard Marston whose comments and feedback helped improve this paper. We also thank Balázs Fekete for helpful discussions regarding potential dam and reservoir construction. This work was supported by the National Science Foundation Belmont Forum Coastal Vulnerability program [#1342944] and the National Aeronautics and Space Administration Land Cover/Land Use Change program [#NNX12AD28G].

References

- A, G., Wahr, J., Zhong, S., 2013. Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: an application to Glacial Isostatic Adjustment in Antarctica and Canada. *Geophys. J. Int.* 192, 557–572.
- Adler, R.F., Huffman, G.J., Chang, A., Ferraro, R., Xie, P.-P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P., Nelkin, E., 2003. The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeorol.* 4:1147–1167. [https://doi.org/10.1175/1525-7541\(2003\)004<1147:TVGPCP>2.0.CO;2](https://doi.org/10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2).
- Amante, C., Eakins, B.W., 2009. ETOP01 1 Arc-Minute Global Relief Mode: Procedures, Data Sources and Analysis.
- Badano, N.D., Sabarots Gerbec, M., Re, M., Menendez, A.N., 2012. A coupled hydro-sedimentological model to assess the advance of the Parana River Delta Front. In: Munoz, R.M. (Ed.), *River Flow 2012*. vols. 1 and 2. CRC Press-Taylor & Francis Group, 6000 Broken Sound Parkway NW, STE 300, Boca Raton, FL 33487-2742 USA, pp. 557–564.
- Baten, M.A., Titumir, R.A.M., 2016. Environmental challenges of trans-boundary water resources management: the case of Bangladesh. *Sustain. Water Resour. Manag.* 2: 13–27. <https://doi.org/10.1007/s40899-015-0037-0>.
- Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nat. Geosci.* 2:488–491. <https://doi.org/10.1038/ngeo0553>.
- Brain, M.J., 2016. Past, present and future perspectives of sediment compaction as a driver of relative sea level and coastal change. *Curr. Clim. Chang. Rep.* 2:75–85. <https://doi.org/10.1007/s40641-016-0038-6>.
- Brakenridge, G.R., Syvitski, J.P., Niebuhr, E., Overeem, I., Higgins, S.A., Kettner, A., Prades, L., 2016. Design with nature: causation and avoidance of catastrophic flooding, Myanmar. *Earth Sci. Rev.* 165:81–109. <https://doi.org/10.1016/j.earscirev.2016.12.009>.
- Center for International Earth Science Information Network, 2016. Gridded Population of the World, Version 4 (GPWv4): Population Density. <https://doi.org/10.7927/H4NF2DQJ>.
- Chaussard, E., Amelung, F., Abidin, H., Hong, S.H., 2013. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sens. Environ.* 128:150–161. <https://doi.org/10.1016/j.rse.2012.10.015>.
- Church, J.A., White, N.J., 2011. Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.* 32:585–602. <https://doi.org/10.1007/s10712-011-9119-1>.
- Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., Unnikrishnan, A.S., 2013. Sea Level Change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: pp. 1137–1216 <https://doi.org/10.1017/CBO9781107415324.026>.
- Cohen, S., Kettner, A.J., Syvitski, J.P.M., 2013. WBMsed, a distributed global-scale riverine sediment flux model: model description and validation. *Comput. Geosci.* 53:80–93. <https://doi.org/10.1016/j.cageo.2011.08.011>.
- Darby, S.E., Dunn, F.E., Nicholls, R.J., Rahman, M., Riddy, L., 2015. A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges-Brahmaputra-Meghna delta. *Environ. Sci.: Processes Impacts* 17: 1587–1600. <https://doi.org/10.1039/c5em00252d>.
- Davie, J.C.S., Falloon, P.D., Kahana, R., Dankers, R., Betts, R., Portmann, F.T., Wisser, D., Clark, D.B., Ito, A., Masaki, Y., Nishina, K., Fekete, B., Tessler, Z., Wada, Y., Liu, X., Tang, Q., Hagemann, S., Stacke, T., Pavlick, R., Schaphoff, S., Gosling, S.N., Franssen, W., Arnell, N., 2013. Comparing projections of future changes in runoff from hydrological and biome models in ISI-MIP. *Earth Syst. Dynam.* 4:359–374. <https://doi.org/10.5194/esd-4-359-2013>.
- Day, J.W., Agboola, J., Chen, Z., D'Elia, C., Forbes, D.L., Giosan, L., Kemp, P., Kuenzer, C., Lane, R.R., Ramachandran, R., Syvitski, J., Yañez-Arancibia, A., 2016. Approaches to defining deltaic sustainability in the 21st century. *Estuar. Coast. Shelf Sci.* 183. <https://doi.org/10.1016/j.ecss.2016.06.018>.
- Doyle, M.W., Stanley, E.H., Harbor, J.M., Grant, G.S., 2003. Dam removal in the United States: emerging needs for science and policy. *EOS Trans. Am. Geophys. Union* 84: 29–33. <https://doi.org/10.1029/2003EO040001>.
- Dunne, J.P., John, J.G., Adcroft, A.J., Griffies, S.M., Hallberg, R.W., Shevliakova, E., Stouffer, R.J., Cooke, W., Dunne, K.A., Harrison, M.J., Krasting, J.P., Malyshev, S.L., Milly, P.C.D., Philipps, P.J., Sentman, L.T., Samuels, B.L., Spelman, M.J., Winton, M., Wittenberg, A.T., Zadeh, N., 2012. GFDL's ESM2 global coupled climate-carbon earth system models. Part I: physical formulation and baseline simulation characteristics. *J. Clim.* 25:6646–6665. <https://doi.org/10.1175/JCLI-D-11-00560.1>.

- Dürr, H.H., Meybeck, M., Dürr, S.H., 2005. Lithologic composition of the Earth's continental surfaces derived from a new digital map emphasizing riverine material transfer. *Glob. Biogeochem. Cycles* 19. <https://doi.org/10.1029/2005GB002515>.
- Edmonds, D.A., Slingerland, R.L., 2009. Significant effect of sediment cohesion on delta morphology. *Nat. Geosci.* 3:105–109. <https://doi.org/10.1038/ngeo730>.
- Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. *Glob. Planet. Chang.* 50, 63–82.
- FAO, 1974. *Soil Map of the World*. Paris.
- Fekete, B.M., Vörösmarty, C.J., Lammers, R.B., 2001. Scaling gridded river networks for macroscale hydrology: development, analysis, and control of error. *Water Resour. Res.* 37, 1955–1967.
- Fetter, C.W., 2001. *Applied Hydrogeology*. 4th ed. Prentice Hall.
- Finer, M., Jenkins, C.N., 2012. Proliferation of hydroelectric dams in the Andean amazon and implications for Andes-amazon connectivity. *PLoS One* 7:1–9. <https://doi.org/10.1371/journal.pone.0035126>.
- Fischer, G., Nachtergaele, F., Prieler, S., van Velthuisen, H.T., 2008. *Global Agro-ecological Zones Assessment for Agriculture*. Laxenburg, Austria and Rome, Italy.
- Giosan, L., Syvitski, J., Constantinescu, S., Day, J., 2014. Protect the world's deltas. *Nature* 516:31–33. <https://doi.org/10.1038/516031a>.
- Goodbred, S.L., Kuehl, S.A., 1998. Floodplain processes in the Bengal Basin and the storage of Ganges-Brahmaputra river sediment: an accretion study using ^{137}Cs and ^{210}Pb geochronology. *Sediment. Geol.* 121:239–258. [https://doi.org/10.1016/S0037-0738\(98\)00082-7](https://doi.org/10.1016/S0037-0738(98)00082-7).
- Grumbine, R.E., Pandit, M.K., 2013. Threats from India's Himalaya dams. *Science* 339: 36–37. <https://doi.org/10.1126/science.1227211> (80–).
- Grumbine, R.E., Xu, J., 2011. Mekong hydropower development. *Science* 332:178–179. <https://doi.org/10.1126/science.1200990> (80–).
- Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. *Proc. Natl. Acad. Sci.* 111:3251–3256. <https://doi.org/10.1073/pnas.1222475110>.
- Hempel, S., Frieler, K., Warszawski, L., Schewe, J., Piontek, F., 2013. A trend-preserving bias correction - the ISI-MIP approach. *Earth Syst. Dynam.* 4:219–236. <https://doi.org/10.5194/esd-4-219-2013>.
- Higgins, S.A., 2016. Review: advances in delta-subsidence research using satellite methods. *Hydrogeol. J.* 24:587–600. <https://doi.org/10.1007/s10040-015-1330-6>.
- Higgins, S., Overeem, I., Tanaka, A., Syvitski, J.P.M., 2013. Land subsidence at aquaculture facilities in the Yellow River delta, China. *Geophys. Res. Lett.* 40:3898–3902. <https://doi.org/10.1002/grl.50758>.
- Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U. S. A.* 111:3292–3297. <https://doi.org/10.1073/pnas.1222469111>.
- Holzer, T.L., Johnson, A.L., 1985. Land subsidence caused by ground water withdrawal in urban areas. *Geojournal* 11:245–255. <https://doi.org/10.1007/BF00186338>.
- Hori, K., Saito, Y., 2007. An early Holocene sea-level jump and delta initiation. *Geophys. Res. Lett.* 34:2–6. <https://doi.org/10.1029/2007GL031029>.
- International Commission on Large Dams, 2009. *World Register of Dams*.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* 77, 437–471.
- Kettner, A.J., Restrepo, J.D., Syvitski, J.P.M., 2010. A spatial simulation experiment to replicate fluvial sediment fluxes within the Magdalena River Basin, Colombia. *J. Geol.* 118: 363–379. <https://doi.org/10.1086/652659>.
- Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V.Q., Dech, S., 2012. Understanding the impact of hydropower developments in the context of upstream-downstream relations in the Mekong river basin. *Sustain. Sci.* 8:565–584. <https://doi.org/10.1007/s11625-012-0195-z>.
- Lehner, B., Verdin, K., Jarvis, A., 2008. New global hydrography derived from spaceborne elevation data. *EOS Trans. Am. Geophys. Union* 89:93–94. <https://doi.org/10.1029/2008EO100001>.
- Lehner, B., Liermann, C.R., Revenga, C., Voerösmarty, C., Fekete, B., Crouzet, P., Doell, P., Eneman, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Roedel, R., Sinding, N., Wisser, D., 2011. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management RID A-3784-2009. *Front. Ecol. Environ.* 9: 494–502. <https://doi.org/10.1890/100125>.
- Liang, M., Dyk, C. Van, Passalacqua, P., 2016a. Quantifying the patterns and dynamics of river deltas under conditions of steady forcing and relative sea level rise. *J. Geophys. Res. Earth Surf.* 121:465–496. <https://doi.org/10.1002/2015JF003653>.Received.
- Liang, M., Kim, W., Passalacqua, P., 2016b. How much subsidence is enough to change the morphology of river deltas? *J. Geophys. Res. Earth Surf.* 121:10266–10276. <https://doi.org/10.1002/2016GL070519>.Received.
- Meckel, T.A., 2008. An attempt to reconcile subsidence rates determined from various techniques in southern Louisiana. *Quat. Sci. Rev.* 27:1517–1522. <https://doi.org/10.1016/j.quascirev.2008.04.013>.
- Milliman, J.D., 1997. Effect of terrestrial processes and human activities on river discharge, and their impact on the coastal zone. In: Haq, B.U., Haq, S.M., Kullenberg, G., Stel, J.H. (Eds.), *Coastal Zone Management Imperative for Maritime Developing Nations*. Springer Netherlands, Dordrecht: pp. 75–92 https://doi.org/10.1007/978-94-017-1066-4_5.
- Morehead, M.D., Syvitski, J.P., Hutton, E.W.H., Peckham, S.D., 2003. Modeling the temporal variability in the flux of sediment from ungauged river basins. *Glob. Planet. Chang.* 39, 95–110.
- Nardin, W., Edmonds, D.A., Fagherazzi, S., 2016. Influence of vegetation on spatial patterns of sediment deposition in deltaic islands during flood. *Adv. Water Resour.* 93: 236–248. <https://doi.org/10.1016/j.advwatres.2016.01.001>.
- Nicholls, R.J., Cazenave, A., 2010. Sea level rise and its impact on coastal zones. *Science* 328:1517–1520. <https://doi.org/10.1126/science.1185782> (80–).
- Pacca, S., 2007. Impacts from decommissioning of hydroelectric dams: a life cycle perspective. *Clim. Chang.* 84:281–294. <https://doi.org/10.1007/s10584-007-9261-4>.
- Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. *Annu. Rev. Earth Planet. Sci.* 32:111–149. <https://doi.org/10.1146/annurev.earth.32.082503.144359>.
- Phien-wej, N., Gao, P.H., Nutalaya, P., 2006. Land subsidence in Bangkok, Thailand. *Eng. Geol.* 82:187–201. <https://doi.org/10.1016/j.enggeo.2005.10.004>.
- Pohl, M.M., 2002. Bringing down our dams: trends in American dam removal rationales. *J. Am. Water Resour. Assoc.* 38:1511–1519. <https://doi.org/10.1111/j.1752-1688.2002.tb04361.x>.
- Rao, K.N., Saito, Y., Nagakumar, K.Ch.V., Demudu, G., Rajawat, A.S., Kubo, S., Li, Z., 2015. Palaeogeography and evolution of the Godavari delta, east coast of India during the Holocene: an example of wave-dominated and fan-delta settings. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 440:213–233. <https://doi.org/10.1016/j.paleaeo.2015.09.006>.
- Renwick, W.H., Smith, S.V., Bartley, J.D., Buddemeier, R.W., 2005. The role of impoundments in the sediment budget of the nonindustrial United States. *Geomorphology* 71:99–111. <https://doi.org/10.1016/j.geomorph.2004.01.010>.
- Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L.D., Wang, F., 2013. Observations: ocean. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: pp. 255–316 <https://doi.org/10.1017/CBO9781107415324.010>.
- Stanley, D.J., Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science* 265:228–231. <https://doi.org/10.1126/science.265.5169.228>.
- Syvitski, J., Milliman, J., 2007. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *J. Geol.* 115, 1–19.
- Syvitski, J.P.M., Kettner, A.J., Correggiari, A., Nelson, B.W., 2005. Distributary channels and their impact on sediment dispersal. *Mar. Geol.* 222, 75–94.
- Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. *Nat. Geosci.* 2:681–686. <https://doi.org/10.1038/ngeo629>.
- Tejedor, A., Longjas, A., Zaliapin, I., Foufoula-Georgiou, E., 2015a. Delta channel networks: 1. Metrics of topological and dynamic complexity for delta comparison, physical inference, and vulnerability assessment. *Water Resour. Res.* 51:3998–4018. <https://doi.org/10.1002/2014WR016604>.Delta.
- Tejedor, A., Longjas, A., Zaliapin, I., Foufoula-Georgiou, E., 2015b. Delta channel networks: 2. Metrics of topological and dynamic complexity for delta comparison, physical inference, and vulnerability assessment. *Water Resour. Res.* 51:4019–4045. <https://doi.org/10.1002/2014WR016577>.Delta.
- Tejedor, A., Longjas, A., Caldwell, R., Edmonds, D.A., Zaliapin, I., Foufoula-Georgiou, E., 2016. Quantifying the signature of sediment composition on the topologic and dynamic complexity of river delta channel networks and inferences toward delta classification. *Geophys. Res. Lett.* 43:3280–3287. <https://doi.org/10.1002/2016GL068210>.Received.
- Tessler, Z.D., Vörösmarty, C.J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J.P.M., Foufoula-Georgiou, E., 2015. Profiling risk and sustainability in coastal deltas of the world. *Science* 349:638–643. <https://doi.org/10.1126/science.aab3574>.
- Tessler, Z.D., Vörösmarty, C.J., Grossberg, M., Gladkova, I., Aizenman, H., 2016. A global empirical typology of anthropogenic drivers of environmental change in deltas. *Sustain. Sci.* 11:525–537. <https://doi.org/10.1007/s11625-016-0357-5>.
- Tornqvist, T.E., Wallace, D.J., Storms, J.E.A., Wallinga, J., van Dam, R.L., Blaauw, M., Derksen, M.S., Klerks, C.J.W., Meijneken, C., Snijders, E.M.A., 2008. Mississippi delta subsidence primarily caused by compaction of Holocene strata. *Nat. Geosci.* 1, 173–176.
- USGS World Energy Assessment Team, 2000. *World Petroleum Assessment*.
- van Asselen, S., 2011. The contribution of peat compaction to total basin subsidence: implications for the provision of accommodation space in organic-rich deltas. *Basin Res.* 23:239–255. <https://doi.org/10.1111/j.1365-2117.2010.00482.x>.
- van Asselen, S., Stouthamer, E., van Asch, T.W.J., 2009. Effects of peat compaction on delta evolution: a review on processes, responses, measuring and modeling. *Earth Sci. Rev.* 92:35–51. <https://doi.org/10.1016/j.earscirev.2008.11.001>.
- Vente, J. De, Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Rompaey, A. Van, Arabkhedri, M., Boix-fayos, C., 2013. Predicting soil erosion and sediment yield at regional scales: where do we stand? *Earth Sci. Rev.* 127:16–29. <https://doi.org/10.1016/j.earscirev.2013.08.014>.
- Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, J.P., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Glob. Planet. Chang.* 39:169–190. [https://doi.org/10.1016/S0921-8181\(03\)00023-7](https://doi.org/10.1016/S0921-8181(03)00023-7).
- Wada, Y., Bierkens, M.F.P., 2014. Sustainability of global water use: past reconstruction and future projections. *Environ. Res. Lett.* 9, 104003. <https://doi.org/10.1088/1748-9326/9/10/104003>.
- Wada, Y., van Beek, L.P.H., Bierkens, M.F.P., 2012. Nonsustainable groundwater sustaining irrigation: a global assessment. *Water Resour. Res.* 48, W00L06. <https://doi.org/10.1029/2011WR010562>.
- Wanner, H., Beer, J., Bütikofer, J., Crowley, T.J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Küttel, M., Müller, S.A., Prentice, I.C., Solomina, O.,

- Stocker, T.F., Tarasov, P., Wagner, M., Widmann, M., 2008. Mid- to Late Holocene climate change: an overview. *Quat. Sci. Rev.* 27:1791–1828. <https://doi.org/10.1016/j.quascirev.2008.06.013>.
- Wilson, C.A., Goodbred Jr., S.L., 2015. Construction and Maintenance of the Ganges-Brahmaputra-Meghna Delta: Linking Process, Morphology, and Stratigraphy. *Annu. Rev. Mar. Sci.* 7:67–88. <https://doi.org/10.1146/annurev-marine-010213-135032>.
- Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., Darwall, W., Lujan, N.K., Harrison, I., Stiassny, M.L.J., Silvano, R.A.M., Fitzgerald, D.B., Pelicice, F.M., Agostinho, A.A., Gomes, L.C., Albert, J.S., Baran, E., Petrere, M., Zarfl, C., Mulligan, M., Sullivan, J.P., Arantes, C.C., Sousa, L.M., Koning, A.A., Hoeninghaus, D.J., Sabaj, M., Lundberg, J.G., Armbruster, J., Thieme, M.L., Petry, P., Zuanon, J., Vilara, G.T., Snoeks, J., Ou, C., Rainboth, W., Pavanelli, C.S., Akama, A., van Soesbergen, A., Sáenz, L., 2016. **Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong.** *Science* 351, 128–129 (80-).
- Wisser, D., Fekete, B., Vörösmarty, C., Schumann, A., 2010a. **Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network-Hydrology (GTN-H).** *Hydrol. Earth Syst. Sci.* 14, 1–24.
- Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Schumann, A.H., Vörösmarty, C.J., 2010b. The significance of local water resources captured in small reservoirs for crop production – a global-scale analysis. *J. Hydrol.* 384:264–275. <https://doi.org/10.1016/j.jhydrol.2009.07.032>.
- Yao, Y., Zhang, B., Ma, X., Ma, P., 2006. Large-scale hydroelectric projects and mountain development on the upper Yangtze River. *Mt. Res. Dev.* 26:109–114. [https://doi.org/10.1659/0276-4741\(2006\)26\[109:LHPAMD\]2.0.CO;2](https://doi.org/10.1659/0276-4741(2006)26[109:LHPAMD]2.0.CO;2).
- Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. *Aquat. Sci.* 77:161–170. <https://doi.org/10.1007/s00027-014-0377-0>.