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LETTER

Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress

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Abstract

Deltas are resource rich, low-lying areas where vulnerability to flooding is exacerbated by natural and anthropogenically induced subsidence and geocentric sea-level rise, threatening the large populations often found in these settings. Delta 'drowning' is potentially offset by deposition of sediment on the delta surface, making the delivery of fluvial sediment to the delta a key balancing control in offsetting relative sea-level rise, provided that sediment can be dispersed across the subaerial delta. Here we analyse projected changes in fluvial sediment flux over the 21st century to 47 of the world's major deltas under 12 environmental change scenarios. The 12 scenarios were constructed using four climate pathways (Representative Concentration Pathways 2.6, 4.5, 6.0 and 8.5), three socioeconomic pathways (Shared Socioeconomic Pathways 1, 2 and 3), and one reservoir construction timeline. A majority (33/47) of the investigated deltas are projected to experience reductions in sediment flux by the end of the century, when considering the average of the scenarios, with mean and maximum declines of 38% and 83%, respectively, between 1990–2019 and 2070–2099. These declines are driven by the effects of anthropogenic activities (changing land management practices and dam construction) overwhelming the effects of future climate change. The results frame the extent and magnitude of future sustainability of major global deltas. They highlight the consequences of direct (e.g. damming) and indirect (e.g. climate change) alteration of fluvial sediment flux dynamics and stress the need for further in-depth analysis for individual deltas to aid in developing appropriate management measures.

1. Introduction

The world's deltas account for less than 0.5% of global land area but are home to over 5% of the global population with their fertile soils supporting intensive agriculture and important expanding cities, such that their social and economic importance extends well beyond their immediate locales (Woodroffe *et al* 2006, Syvitski *et al* 2009, Evans 2012). Deltas' low-lying land means that the inhabitants are highly exposed to the threat of rising relative sea level (Ericson *et al* 2006, Syvitski 2008, Ibáñez *et al* 2014). Associated problems,

such as water and soil salinization and land loss, also threaten agricultural productivity and livelihoods, presenting a challenge to future food security (Smajgl *et al* 2015). For these reasons there is a growing concern that accelerated rates of relative sea-level rise (Syvitski *et al* 2009, Tessler *et al* 2018) are presenting the world's deltas with a sustainability crisis (Anthony *et al* 2015, Tessler *et al* 2015, Day *et al* 2016, Tessler *et al* 2016, Kondolf *et al* 2018). Although deltas naturally sink relative to sea level as a result of, for instance, sediment compaction and tectonics, anthropogenic activities such as groundwater abstraction often

induce accelerated subsidence (Chen *et al* 2012, Erban *et al* 2014, Brown and Nicholls 2015, Fujihara *et al* 2015, Higgins 2016, Jones *et al* 2016, Minderhoud *et al* 2017). This accelerated subsidence can be compounded by geocentric sea-level rise in response to climate warming (FitzGerald *et al* 2008, Cazenave and Remy 2011). Indeed, many delta areas are now experiencing rates of relative sea-level rise in excess of 10 mm/a when considering geocentric sea-level rise (Chen *et al* 2014) in combination with land elevation change, where the latter is comprised of subsidence, crustal movement, and accretion (Syvitski *et al* 2009).

The only process that can potentially offset rising relative sea level is sediment accretion. In this paper we assume that delta surface accretion rates are primarily driven by the rate of fluvial sediment delivery from the feeder catchment upstream and the capacity of the delta to retain that sediment (Giosan *et al* 2014, Syvitski *et al* 2005a, Syvitski and Kettner 2011, Ibáñez *et al* 2014). Fluvial sediment delivery is therefore a vital precondition for aggradation, so we focus here on projecting sediment flux at the delta apex as an important, but not exclusive, control on delta aggradation, as aggradation can only occur if the available sediment is deposited within the delta area. Prior studies have highlighted how fluvial sediment delivery is a critical factor in offsetting relative sea-level rise (Syvitski *et al* 2009, Evans 2012, van Asselen *et al* 2017), but these previous studies have focused either on contemporary (Evans 2012, Tessler *et al* 2015) or past (Syvitski *et al* 2005b, Milliman and Meade 1983, Milliman and Syvitski 1992, Guillén and Palanques 1997, Darby *et al* 2016) changes in sediment flux. Few studies have projected future changes in fluvial sediment flux, and those that have were limited to a few rivers (Dunn *et al* 2018) while addressing a single driver of change, such as dam construction (Tessler *et al* 2018) or climate change (Darby *et al* 2015, Praskievicz 2016). Therefore, to our knowledge, no prior study has offered a large-scale perspective of projected changes to the world's major deltas under multiple drivers of environmental change.

Of the drivers of environmental change included here, the influence of reservoir construction on fluvial sediment fluxes has been a notable focus of some prior studies. It has been estimated that reservoirs trap 20%–30% of recent global fluvial sediment fluxes, with large increases in the rate of sediment trapping in the second half of the 20th century (Syvitski *et al* 2005b, Vörösmarty *et al* 2003). Considering this past trajectory, alongside projections of increased large dam construction in the future, it is reasonable to assume that reservoirs will continue to play a key role in determining sediment delivery at the global scale. Global scale analyses provide high level insights into the range of drivers and the extent to which they control future trends in sediment delivery to major deltas. Use of global-scale projection tools (numerical models) and input data, while having a higher degree of
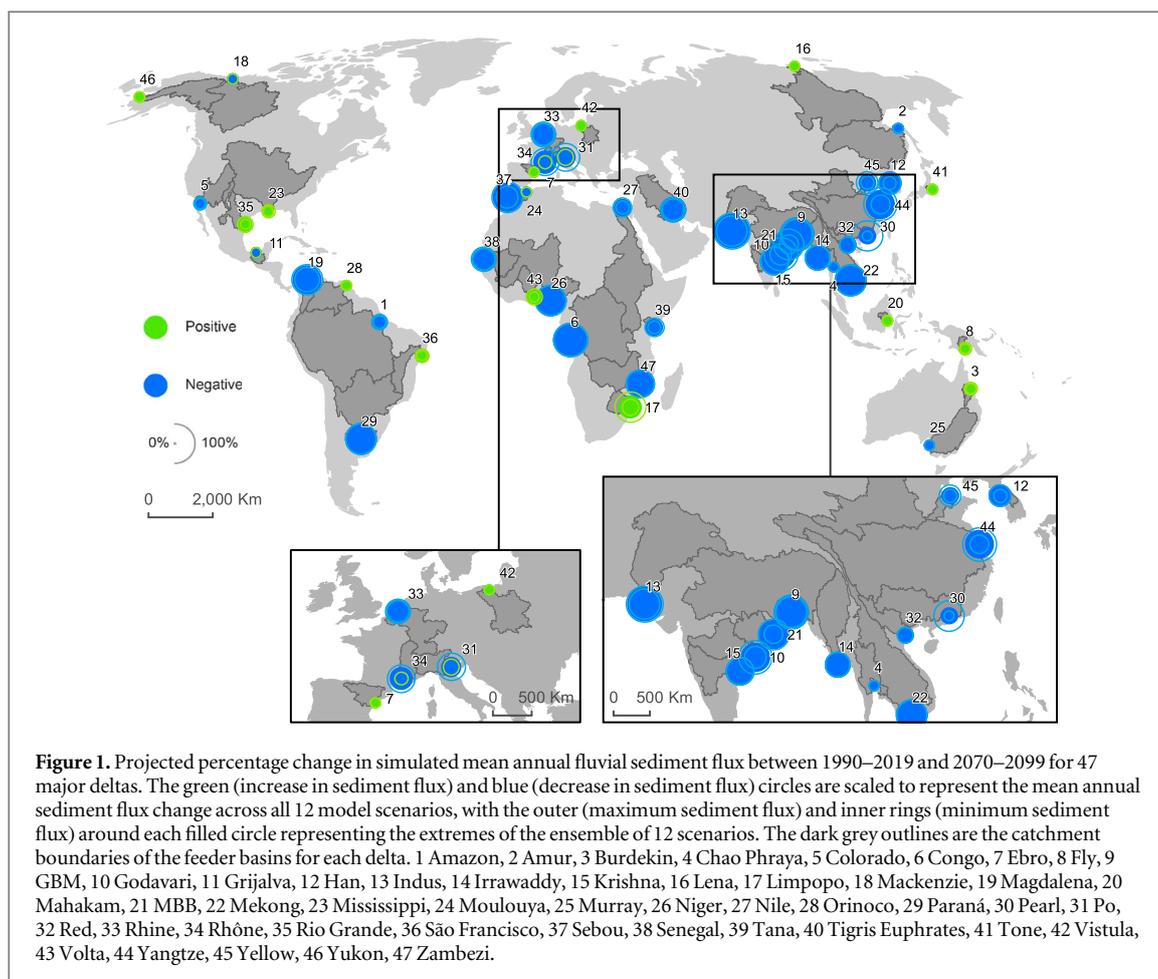
uncertainty relative to delta-specific analysis, offer uniformity in the analysis, facilitating both comparison between deltas and 'global' analysis including ranking. Such modelling tools are necessary to ensure consistency across the variable climate, socio-economic, and especially sediment data in most parts of the world.

2. Methods

Here the spatially explicit hydrogeomorphic model, WBMsed (Cohen *et al* 2013, 2014), is used to project fluvial sediment delivery to 47 of the world's major deltas (supplementary table 2 is available online at stacks.iop.org/ERL/14/084034/mmedia, figure 1) under 12 environmental change scenarios representing the effects of future climate change, socioeconomic development, and dam construction to the end of the 21st century. The 47 deltas were selected from the world's larger deltas to represent a wide range of climates, ecosystems, geomorphologies, population densities, and economic capacities (Tessler *et al* 2015, supplementary table 2). The set of 47 deltas is intended to be analysed as a whole, including asking why different patterns occur, and what are the exceptions. Individual deltas are only named as exemplars to highlight the trends found in the ensemble. The WBMsed model was validated by comparison of simulated versus observed mean annual water and sediment flux data over the period 1990 to 1999 (see section 2.1.1). The 12 environmental change scenarios employed herein were constructed based on combinations of four climate pathways (Jones *et al* 2011) (Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, and 8.5), three population and GDP pathways (Murakami and Yamagata 2016, Shared Socioeconomic Pathways (SSP) 1, 2, and 3), and one projection of future global trends in large dam construction (Lehner *et al* 2011a, 2011b, Zarfl *et al* 2015).

2.1. Hydrogeomorphic model

The spatially and temporally explicit hydrogeomorphic model WBMsed (Cohen *et al* 2013, 2014) was employed to project fluvial sediment fluxes to the 47 selected deltas. Specifically, we employ an updated version (WBMsed v.2.0) which has previously been employed on a global scale (Cohen *et al* 2014), and which better predicts sediment fluxes during high discharge events, demonstrating its suitability for use in this study. WBMsed computes river discharges by solving a water balance that accounts for precipitation, modulated by soil moisture, evapotranspiration, irrigation, floodplain, reservoir, and groundwater storage. The river discharge is then used, along with data on reservoirs, basin area, relief, temperature, glaciers, lithology, population, and gross national product (GNP) per capita to calculate sediment fluxes using the BQART sediment delivery model (Syvitski and

Figure 1. Projected percentage change in simulated mean annual fluvial sediment flux between 1990–2019 and 2070–2099 for 47 major deltas. The green (increase in sediment flux) and blue (decrease in sediment flux) circles are scaled to represent the mean annual sediment flux change across all 12 model scenarios, with the outer (maximum sediment flux) and inner rings (minimum sediment flux) around each filled circle representing the extremes of the ensemble of 12 scenarios. The dark grey outlines are the catchment boundaries of the feeder basins for each delta. 1 Amazon, 2 Amur, 3 Burdekin, 4 Chao Phraya, 5 Colorado, 6 Congo, 7 Ebro, 8 Fly, 9 GBM, 10 Godavari, 11 Grijalva, 12 Han, 13 Indus, 14 Irrawaddy, 15 Krishna, 16 Lena, 17 Limpopo, 18 Mackenzie, 19 Magdalena, 20 Mahakam, 21 MBB, 22 Mekong, 23 Mississippi, 24 Moulouya, 25 Murray, 26 Niger, 27 Nile, 28 Orinoco, 29 Paraná, 30 Pearl, 31 Po, 32 Red, 33 Rhine, 34 Rhône, 35 Rio Grande, 36 São Francisco, 37 Sebou, 38 Senegal, 39 Tana, 40 Tigris Euphrates, 41 Tone, 42 Vistula, 43 Volta, 44 Yangtze, 45 Yellow, 46 Yukon, 47 Zambezi.

Milliman [2007](#)):

$$Q_S = \omega B Q^{0.31} A_B{}^{0.5} R T \text{ when } T \geqslant 2\,°C, \quad (1)$$

$$Q_S = 2\omega B Q^{0.31} A_B{}^{0.5} R \text{ when } T < 2\,°C, \quad (2)$$

where Q_S is the flux of suspended sediment (kg s^{-1}), B is a catchment factor, expanded later, A_B is the drainage basin area (km^2), R is the basin maximum relief (m), T is the spatially averaged basin temperature (°C), Q is the flow discharge (m^3 s^{-1}), and ω is a proportionality coefficient (0.02 for kg s^{-1} or 0.0006 for Mt per year). The catchment factor, B, is estimated using:

$$B = (1 - T_E) G L E_H, \quad (3)$$

where T_E is the trapping efficiency of natural and anthropogenic reservoirs (calculated using Brown ([1944](#)) for small ($<$0.5 km^3) reservoirs and Brune ([1953](#)) and Vörösmarty *et al* ([2003](#)) for larger ($\geqslant$0.5 km^3) water bodies), G is a glacial erosion factor, L is a lithology factor (Dürr *et al* [2005](#), Syvitski and Saito [2007](#)), and E_H is an anthropogenic soil erosion factor. The glacial erosion parameter, G, is defined as:

$$G = 1 + 0.09 A_G, \quad (4)$$

where A_G is the glaciated area of the basin expressed as a percentage of the total catchment area (from Peltier [2004](#)) and employed as a constant input in the model runs.

Table 1. Look-up table for the anthropogenic factor (E_H) as a function of population density and GNP per capita (Syvitski and Milliman [2007](#), Cohen *et al* [2013](#), [2014](#)).

	Population density (persons km^{-2})		
	$<$30	30–140	$>$140
GNP per capita ($)			
$<$2500	1.0	1.0	2.0
2500–20 000	1.0	1.0	1.0
$>$20 000	1.0	0.3	0.3

The soil erosion factor (E_H) values were estimated using look-up tables based on population density and GNP data (table [1](#)). The look-up tables (developed by Syvitski and Milliman [2007](#)) describe how changes in anthropogenic activities, particularly catchment management practices such as land use change and channel engineering, affect sediment flux. In summary these relationships assume: (1) low density populations have no influence on sediment delivery; (2) poorer high density populations increase sediment delivery due to erosion-enhancing land management techniques; (3) richer high density populations employ erosion controlling land management practices and channel engineering, reducing sediment delivery. The basin-lumped

Table 2. Overview of data inputs required by the WBMsed simulations with a summary of data sources employed in this study.

Input	Format	Data source
Flow network	Static grid	Vörösmarty *et al* (2000)
Contributing area	Static grid	Vörösmarty *et al* (2000)
Maximum relief	Static grid	Cohen *et al* (2008)
Minimum slope	Static grid	Vörösmarty *et al* (2000)
Ice cover	Static grid	Cohen *et al* (2013)
Small reservoir capacity	Annual grid	Wisser *et al* (2010)
Irrigation area	Annual grid	Wisser *et al* (2008)
Irrigation intensity	Static grid	Allen *et al* (1998)
Irrigation efficiency	Static grid	Allen *et al* (1998)
Crop fraction	Static grid	Ramankutty and Foley (1999)
Lithology factor	Static grid	Syvitski and Milliman (2007)
Soil parameters	Static grid	Food and Agricultural Organisation Soil Map
Bankfull discharge	Grid and recurrence interval constant	Cohen *et al* (2013)
River bed slope	Constant	Cohen *et al* (2013)
Floodplain to river flow	Constant	Cohen *et al* (2013)

method of representing anthropogenic activities is intended to reflect not just influence on the production of sediment through land use, but also other activities which may affect the passage of sediment downstream such as channel mining and river engineering works. The method is therefore intended to reflect the physical characteristics and anthropogenic activities of the whole basin.

The WBMsed model simulations are undertaken at daily time steps and, in this study, the model was run over a global stream-network grid at 6 arc-min (~11 km at the equator) spatial resolution. This spatial and temporal resolution is appropriate to capture temporal changes in extreme flow conditions (both high and low) due to changes in climatic conditions and dam construction. High-magnitude streamflow events can contribute a large proportion (often the majority) of the long-term sediment flux budget so capturing these events is important. Thus, climate and damming effects on the magnitude and frequency of extreme streamflow can be more consequential to sediment flux dynamics than their effect on average streamflow changes. While uncertainty in these short-term model predictions are relatively high (Cohen *et al* 2014), our analysis is based on long-term relative (decadal) changes. So, although the model may over or under predict sediment flux there is confidence, underpinned by theory and validation, in the relative changes over time as these are driven solely by changes in the simulated scenario.

Mean annual sediment fluxes were extracted from WBMsed projections at the delta apices (supplementary table 2) and then averaged over the decadal periods of interest (1990–2019 and 2070–1099). The delta apices were defined as the point at which each major river enters the delta area (Tessler *et al* 2015). WBMsed was run using the inputs listed in table 2, together with additional datasets to parameterise the scenarios of future changes in sediment load; these additional data sets are detailed in section 2.2, along with an

explanation of the construction of the model scenarios employed.

2.1.1. Validation
The WBMsed model performance was evaluated by comparing the computed mean annual 1990–1999 water and sediment fluxes with observed data, where such observed data are available (see supplementary table 2). When comparing the simulated and observed mean annual water and sediment fluxes, the simulated data are largely within an order of magnitude of the observed data and are clustered around the $y = x$ line (supplementary figure 1). We focus here on relative changes in sediment load and the relative importance of the different drivers of change at a global-scale. While we recognise that uncertainties in the model structure, input data, and observations may preclude a precise replication of sediment flux for an individual basin, the model validation indicates that overall trajectories of change can be established with confidence, as can comparisons of the relative changes both within and between individual basins, so analysis of these relative changes in a global context is a robust presentation of the modelled changes.

2.2. Model scenarios
We constructed a total of 12 future environmental change scenarios based on the combination of four climate change pathways (Jones *et al* 2011, Representative Concentration Pathways, RCPs), three socioeconomic change pathways (Murakami and Yamagata 2016, Shared Socioeconomic Pathways, SSPs), and a single dam construction timeline (Zarfl *et al* 2015). These scenarios enable the impacts of the environmental changes on water and sediment flux to be assessed both in combination and in isolation i.e. for each individual driver pathway of climate change, socioeconomic development, and dam construction. In all cases the simulations are run to the year 2099.

2.2.1. Climate change data

The climate change pathways used in this work are based on the four RCPs (van Vuuren *et al* 2011). The RCPs encompass internally consistent land use, GHG (greenhouse gas) and other atmospheric pollutant emissions and atmospheric concentration data. The climate projections employed here are based on a set of General Circulation Model (Met Office Hadley Centre Global Environment Model version 2—Earth System (HadGEM2-ES), Jones *et al* 2011) simulations forced using these RCPs as well as solar irradiance and stratospheric volcanic aerosols to model historical and future climate projections at 0.5 degree spatial and daily time step resolution for the period 1950–2100 (experiments number 3.2 and 4.1–4.4 in Jones *et al* 2011). The RCPs diverge from 2005 onwards, so the 1950–2004 climate data is the same for all pathways. Mean (daily 0.5° spatial resolution) air temperature (°C) and precipitation (mm/a) are taken from the outputs of the runs of HadGEM2-ES (Jones *et al* 2011) and were used to drive WBMsed for the period 1980 to the end of 2099.

2.2.2. Socioeconomic change data

The scenarios used in this current research incorporate three of the five SSPs, SSP1 to SSP3. The SSPs are narratives which explore a range of plausible scenarios for future global socioeconomic development. The result of these narratives is a collection of pathways which exhibit different climate change mitigation and adaptation challenges (Riahi *et al* 2017). The pathways used in this research, SSP1 to SSP3, have progressively higher challenges for both adaptation and mitigation (O'Neill *et al* 2014). Decadal population and GNP projections by country were created from each of the SSP storylines. The method for the production of the population data is based on the projected fertility, mortality, migration, and education differences between the SSPs (KC and Lutz 2017). The model used for producing the GNP data is based primarily on population demographics, productivity growth, physical capital accumulation, and country-specific factors (Crespo Cuaresma 2015).

The original economic and population projections (Riahi *et al* 2017) are presented at the country scale, however these national-scale data have been disaggregated to 0.5° resolution globally for the period 2020–2100 (Murakami and Yamagata 2016) and it is these data which were used in this research (version 1.0 of the datasets). The downscaling procedures are identical for both the population and GNP data, and were based on an ensemble mean of three deterministic and three stochastic approaches to downscaling to enable the flexible use of multiple auxiliary variables (see Murakami and Yamagata (2016) for details). All downscaling approaches use urban area, urban population, and total road length to determine population per grid cell. The deterministic methods distribute population by weighting those three factors. The

stochastic approaches are geographically weighted regression models, assuming non-stationarity, which incorporates the three previously mentioned factors. The spatially disaggregated socioeconomic data retain the temporal resolution of the original SSP data, giving data for one year per decade (2010, 2020, etc). To allow the data to be input to WBMsed the data for each cell in the spatially disaggregated dataset were linearly interpolated through time, thereby creating annual global datasets.

2.2.3. Reservoir construction data

We employed the global, spatially explicit, projected dam database (Zarfl *et al* 2015), which details hydro-power dams with 1 MW or greater generating capacity which are either under construction or planned. Note that the exclusion of dams under 1 MW capacity, together with the focus on hydropower dams, means that the dataset under-estimates potential future dam construction. The dam database (Zarfl *et al* 2015) includes information on dam location, generating capacity, and construction timeline. In addition, WBMsed requires an estimate of reservoir storage capacity to calculate sediment flux (Syvitski and Milliman 2007). We therefore employed equation (5) to estimate each reservoir's storage capacity from the hydroelectric generating capacity using:

$$K = H_E * 3.19, \qquad (5)$$

where K is the reservoir storage volume (m^3) and H_E is the hydroelectric generating capacity (W, Grill *et al* 2015). Equation (5) is based on information from 251 planned Asian dams.

Existing dams were represented using the GRanD database (Lehner *et al* 2011a, 2011b). For most of the planned dams (Zarfl *et al* 2015) the construction timeline is not available, therfore all planned dams are assumed to be constructed by 2050 and beyond 2050 the reservoir capacity remains unchanged. In reality not all the dams implemented in the model timeline will be built by 2050; some may be built after 2050, in a modified form, or not at all. The future dams dataset used is in some ways an underestimation of total potential future reservoir volume as only hydropower dams with a capacity of more than 1 MW are included. Additional uncertainty is caused by the unknown status of the current and future operational management of each reservoir. Here it is assumed that the reservoirs are all maintained, with no loss of capacity due to sediment deposition, and that no dams are decommissioned or removed. The dam construction pathway that are employed here should be seen as an indicative and realistic description of potential dam provision in the future, but it may not represent the most likely future due to assumptions made about the type and timing of dam construction over the 21st century. However, the timeline used is currently the most robust pathway in terms of integration of available information on a global scale. The single reservoir

construction timeline employed was created using all information available for large planned dams because globally consistency of the scenarios used in this research is essential, and the creation of multiple time-lines would lead to inconsistency at the global scale due to the uncertainties in the likelihood of planned dams being realised.
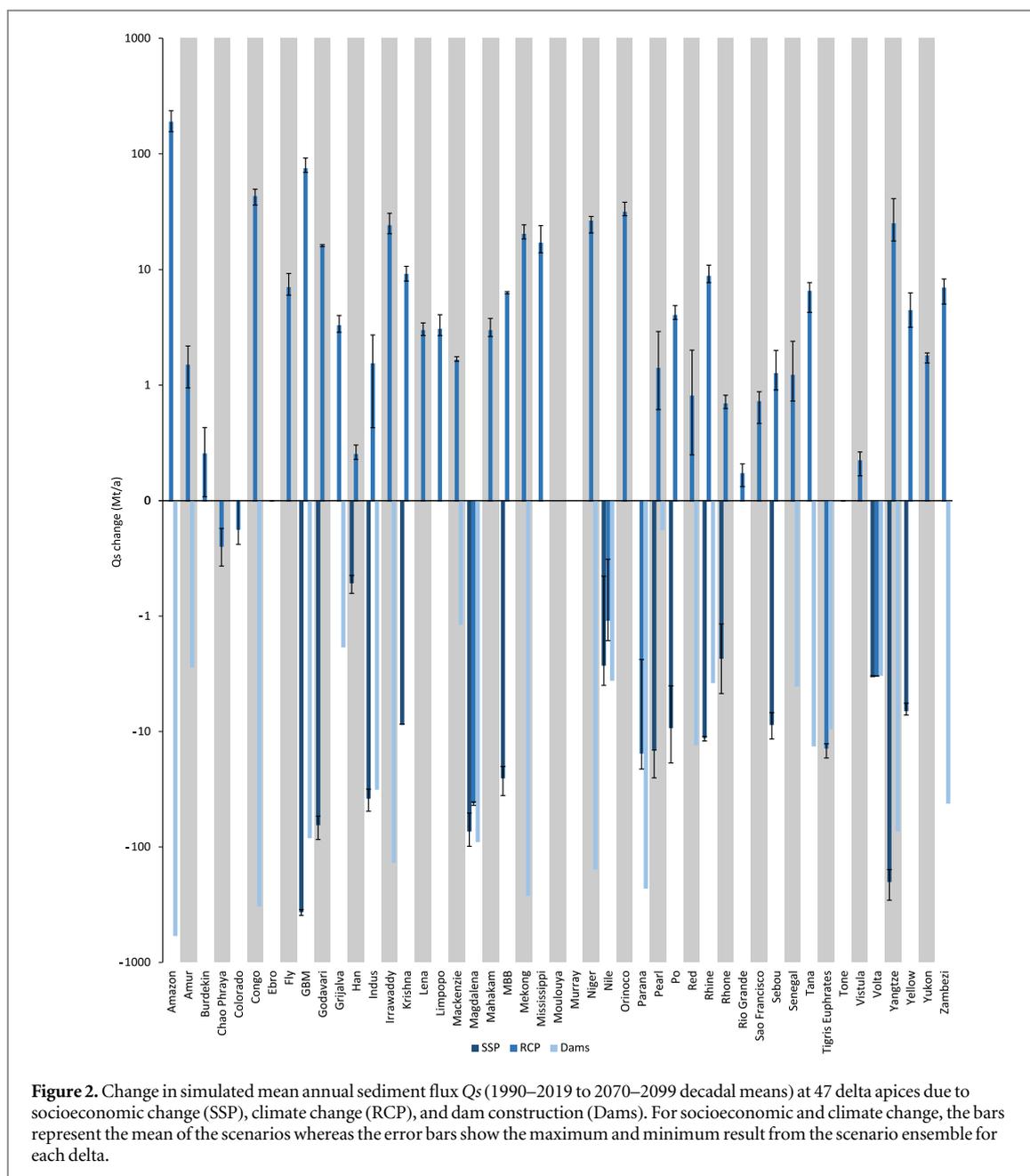
3. Results

The results (figure 1) highlight major changes in the mean annual sediment load delivered to the 47 deltas between the 30 year periods at the start (1990–2019) and end (2070–2099) of the present century. Considering the ensemble mean of the 12 environmental change scenarios across all 47 deltas, mean annual sediment flux is projected to decrease by 38% (a decline of 2500 Mt/a in total, from 6500 to 4000 Mt/a). For individual deltas, the change varies between a reduction of 83% (30 Mt/a) for the Indus to an increase of 49% (3 Mt/a) for the Limpopo. Indeed, much greater variability is seen in the ensemble mean change in projected sediment flux across the 47 deltas than there is in variability between the 12 environmental change scenarios. The range of simulated sediment fluxes across the ensemble of the 12 scenarios (shown for individual deltas on figure 1 and supplementary figure 2) are only 7% (450 Mt/a) of the initial total sediment load. The scenario with the highest socioeconomic challenges (SSP3) and the largest climate change (RCP8.5) produces the smallest decrease in simulated sediment flux (34% or 2300 Mt/a across the 47 deltas), whereas the scenario with the lowest socioeconomic challenges (SSP1) and smallest climate changes (RCP2.6) cause the largest decrease in simulated sediment flux (41% or 2700 Mt/a across the 47 deltas). This is because anthropogenic climate change tends to drive increased sediment flux through increased air temperature and precipitation (see equations (1) and (2) in section 2.1), whereas higher socioeconomic challenges result in higher sediment flux, as less economic development results in poorer land management and higher soil erosion (Syvitski *et al* 2003, Syvitski and Milliman 2007, Kettner and Syvitski 2008a, 2008b, see section 2.1 and table 1).

The changes in projected fluvial sediment delivery vary substantially between deltas depending on the primary driver of change affecting each feeder catchment (figure 2, supplementary figure 3). Taking the mean of the four climate change pathways (figure 2), sediment fluxes to the 47 deltas increase by 7% (500 Mt/a) over the 21st century, with a range of 6%–9% (400–600 Mt/a) depending on the respective climate change scenario (RCP8.5 giving the greatest change and RCP2.6 the least). A total of 39 of the 47 deltas exhibit an increase in sediment flux across all four climate change pathways, with projected increases in temperature over the 21st century for all the climate

pathways being the primary factor for the climate-driven increases in sediment delivery globally, although changes in precipitation also influence sediment fluxes (see equations (1) and (2) in section 2.1). Precipitation changes are variable across the globe and so the effect on runoff generation and sediment transport likewise varies between the delta catchments. Only five deltas (the Chao Phraya, Magdalena, Nile, Parana, and Tigris Euphrates) exhibit a decrease in sediment flux across all four climate change pathways, but for three of these (Chao Phraya, Nile, and Parana) these projected declines are small (<10%). For two deltas (Tigris Euphrates and Magdalena), the projected decline in sediment flux is larger (28% and 26%, respectively) and is forced by a significant decrease in precipitation. For the remaining three deltas (the Colorado, Moulouya, and Murray), the direction of projected sediment flux change is dependent on the specific climate change pathway under consideration. When compared with the other drivers considered here, climate change causes the smallest changes in sediment flux.

The projected socioeconomic changes investigated here drive an overall decrease in fluvial sediment delivery of 11% (700 Mt/a) in the mean of the three socioeconomic scenarios, but 31 of the 47 deltas experience no change in sediment load as a result of socioeconomic change (figure 2). The majority of deltas are unaffected by socioeconomic change because either there is no change in socioeconomic classification in the catchment over the course of the 21st century e.g. Congo, Lena, Mississippi, or because counteracting changes occur which neutralise the overall effect e.g. Nile, Volta, Yellow. For example, such a neutralising effect can occur as a result of an initial increase in population density driving an increase in sediment delivery that is later counter-balanced by increasing wealth driving a decline in sediment delivery (see table 1). For the 16 deltas that are affected by socioeconomic changes, the mean change in sediment delivery ranges between −8% and −86% across the three socioeconomic pathways. For 11 of these 16 affected deltas, sediment loads are projected to decline in all of the socioeconomic pathways, however for four of these deltas (Magdalena, Pearl, Po, and Rhône) there is no change under SSP3 and for one (Volta) there is no change under two of the socioeconomic pathways (SSP2 and SSP3). The differences between socioeconomic pathways arise because those pathways with higher socioeconomic challenges (SSP3) have less socioeconomic development and therefore less influence on catchment erosion. Importantly, for 13 of the 16 deltas that are affected by projected socioeconomic change, the scale of the impact on reduced sediment load is greater than the increase in flux driven by future climate change.
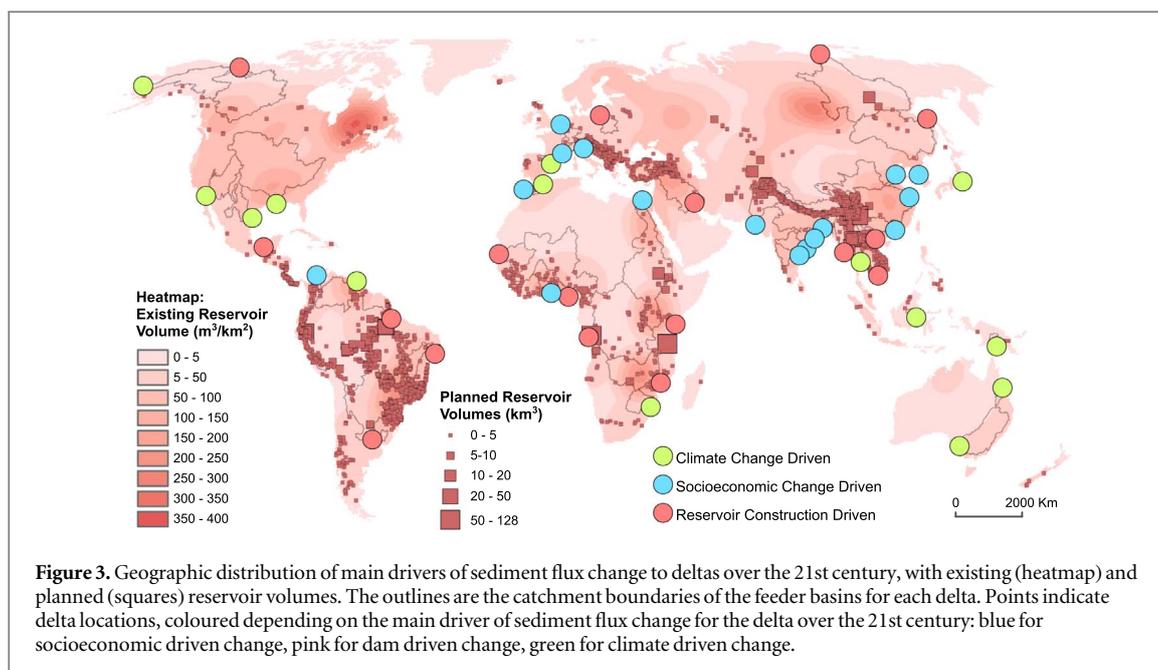
Dam construction induces major change in future sediment flux, with the dam construction scenario driving an overall 30% (2000 Mt/a) decrease in fluvial sediment flux for the 26 deltas affected by dam

Figure 2. Change in simulated mean annual sediment flux *Qs* (1990–2019 to 2070–2099 decadal means) at 47 delta apices due to socioeconomic change (SSP), climate change (RCP), and dam construction (Dams). For socioeconomic and climate change, the bars represent the mean of the scenarios whereas the error bars show the maximum and minimum result from the scenario ensemble for each delta.

construction over the 21st century (figure 2). For 17 of the 47 deltas investigated here, dam construction is therefore the key driver of the projected decrease in sediment flux, overwhelming the influence of climate change and often (for 15 of the 17 deltas) exceeding the effects of projected socioeconomic development in every pathway.

The relative influence of climate change, socioeconomic development, and dam construction on the sediment flux reaching the deltas, when combined with knowledge of the global spatial distribution of these driving factors, affords insight into regional response and risk factors (figure 3). There are several clusters of deltas, for instance in Central and South America, Africa, and in the high latitudes, where dam construction is projected to be the dominant factor driving reduced sediment loads in the 21st century.

For these deltas, closer scrutiny of the adverse impacts of planned dams, when combined with sediment flushing measures, could allow mitigation of some of the worst projected declines in the downstream transmission of fluvial sediment. Other clusters of deltas, notably in Asia and Europe, have sediment loads dominantly impacted by projected future socioeconomic development. Lastly, there are clusters of deltas for which the key driver of future sediment flux change is climate change, due to a lack of projected anthropogenic disturbance over the 21st century. Climate change dominates the response of these deltas either because their low populations reduce the significance within the model of future socioeconomic change (Australasia), or because their catchments have already been extensively impacted by anthropogenic activity such as dam construction (North America).

Figure 3. Geographic distribution of main drivers of sediment flux change to deltas over the 21st century, with existing (heatmap) and planned (squares) reservoir volumes. The outlines are the catchment boundaries of the feeder basins for each delta. Points indicate delta locations, coloured depending on the main driver of sediment flux change for the delta over the 21st century: blue for socioeconomic driven change, pink for dam driven change, green for climate driven change.

4. Conclusions

Our projections show major declines in fluvial sediment supply to many of the world's major deltas over the remainder of this century. On average across the environmental change scenarios, mean sediment supply to the 47 major deltas decreases by 38% (2500 Mt/a) between 1990–2019 and 2070–2099, with a range of 34%–41% dependent on scenario. In the average of the scenarios, 33 of the 47 deltas are projected to experience in decrease supply. Dam construction is projected to cause the largest changes in sediment supply, decreasing delivery to the deltas by 30% (2000 Mt/a), however socioeconomic change can be just as significant for individual deltas while only causing an overall decrease of 7%–12% (500–800 Mt/a). Climate change drives the smallest changes, causing a 6%–9% (400–600 Mt/a) increase in sediment supply depending on the pathway. While quantification of the effects of these global drivers is novel, the reduction in sediment flux due to reservoir construction is not surprising considering the global history of sediment interception by dams (Vörösmarty *et al* 2003, Syvitski *et al* 2005b) and projections of planned dams into the future (Zarfl *et al* 2015).

Considering the limitations of the current research, there are particular actions which could be taken to further explore the subtleties of the methodology and results. Firstly, there is the potential to improve the link between anthropogenic activities and fluvial sediment fluxes. The current relationship uses proxies in the form of wealth and population density, and developments could include relationships between specific anthropogenic actions such as land management and river sediment. Secondly, a key result of this research is the importance of reservoir construction for sediment delivery. Further work on

scenarios of reservoir construction is crucial to reduce the uncertainty inherent in this vital factor. Uncertainties arise due to the difficulties in creating scenarios of reservoir construction which are globally consistent with regards to which dams are built where and in what form, as well as maintenance regimes and potential dam removal. An additional aspect of scenario construction which has the potential for further development is the inclusion of glacial influence on sediment delivery. The current model assumes a time-invariant glacier area, which in future work could be updated to include more recent datasets (e.g. RGI Consortium 2017, Maussion *et al* 2019) as well as to include dynamic projections of glacier area under various climate scenarios.

The specific implications of the declines in sediment supply for individual deltas depend on the rates of change of other key controlling factors, such as subsidence and geocentric sea-level rise, as well as the current and future rates of sediment retention on deltas. The potential for sediment to be retained on deltas is, along with a supply of fluvial sediment from upstream, a vital prerequisite for delta aggradation. Anthropogenic activities within delta areas are often incompatible with, or preclude, the flooding necessary for sediment deposition, or actively inhibit access to the land surface for sediment deposition, for example due to the presence of urban infrastructure. Without the ability to retain the supply of available sediment on the delta surface, deltas will be unable to avoid relative sea level rise. This and other factors should be investigated in more detail using delta-specific analysis.

Notwithstanding the uncertainties inherent in estimating future rates of relative sea-level rise, the declines in future sediment load projected here are sufficiently large and consistent to raise concerns about the future of deltas. These results suggest potentially major adverse impacts,

including accelerated loss of elevation and 'delta drowning', or a growing dependency on dikes and pumped drainage as exemplified by the Netherlands. Hence, there is now a clear imperative to mitigate declining fluvial sediment loads to minimise such impacts. Importantly for such mitigation efforts, our research highlights that anthropogenic climate change is the least influential driver of sediment flux change investigated here. Rather, the key drivers of future reduced fluvial sediment loads are anthropogenic activities occurring within each of the delta's catchments, primarily increased dam construction. While the scale of the challenge is significant, this means that nations hosting the world's deltas and their associated catchments, as well as relevant international organizations e.g. United Nations, World Bank, should consider sediment management, including measures to minimise sediment flux reductions detrimental to downstream delta sustainability. This consideration is a logical extension of integrated delta management planning which is becoming more widespread (Seijger *et al* 2016).

Acknowledgments

Data availability statement

The model results are available through the Delta Portal (http://delta-portal.net). The model code is available on the CSDMS model repository (https://csdms.colorado.edu/wiki/Model:WBMsed) and additional model predictions are available on the SDML data repository (https://sdml.ua.edu/datasets-2).

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