

## Future impacts of freshwater resource management: sensitivity of coastal deltas

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**Abstract** We present an assessment of contemporary and future effective sea-level rise (ESLR) using a sample of 40 deltas distributed worldwide. For any delta, ESLR is a net rate defined by eustatic sea-level rise, natural gross rates of fluvial sediment deposition and subsidence, and accelerated subsidence due to groundwater and hydrocarbon extraction. Present-day ESLR, estimated from geospatial data and a simple model of deltaic dynamics, ranges from 0.5 to 12.5 mm year<sup>-1</sup>. Reduced accretion of fluvial sediment from upstream siltation of reservoirs and freshwater consumptive irrigation losses are primary determinants of ESLR in nearly 70% of the deltas, while for only 12% eustatic sea-level rise predominates. Future scenarios indicate a much larger impact on deltas than previously estimated. Serious challenges to human occupancy of deltas worldwide are conveyed by upland watershed factors, which have been studied less comprehensively than the climate change and sea-level rise question.

**Key words** deltas; sea-level rise; sediment flux; water resource management; siltation; reservoirs

### INTRODUCTION

Deltas are dynamic coastal systems, unique in their close links to both land-based and coastal ocean processes. With adequate fluvial sediment supply and minimal human influence, deltas generally maintain their integrity and/or continue to extend seaward (Sanchez-Arcilla *et al.*, 1998). Increased sediment load associated with the rise of upland agriculture and land clearing has accelerated the growth of many deltas over the past 2000 years (McManus, 2002), while more recently, pandemic construction of reservoirs and freshwater diversions have generally decreased net sediment loads of rivers including those feeding deltas (Walling & Fang, 2003; Vörösmarty *et al.*, 2003; Syvitski *et al.*, 2005). This decrease, along with isostatic loading factors, sediment compaction and accelerated subsidence of deltaic sediments resulting from local groundwater withdrawal and hydrocarbon extraction, has moved many deltas from a condition of active growth to a destructive phase (Milliman *et al.*, 1989; McManus, 2002; Poulos & Collins, 2002). The hazard is compounded by the global historical

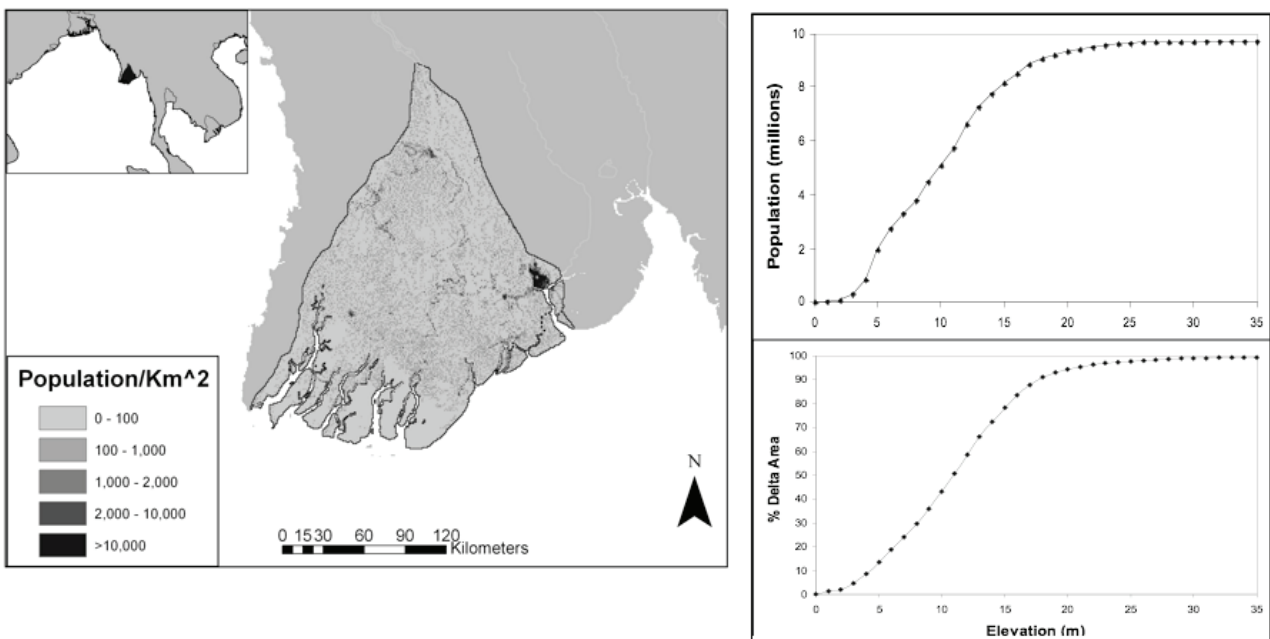
trend in eustatic sea-level rise and predictions of increasing rates of sea-level rise over the next century (Church & Gregory, 2001).

This paper has two goals. The first is to identify the principal factors determining contemporary rates of effective sea-level rise (ESLR) across a sample of 40 of the world's deltas. Our approach considers the fluvial, coastal and oceanic contributions to this change. The second goal is to evaluate implications of these trends over the next half-century.

## METHODS

We created a digital data set of delta extents mapped at 30 arc-second latitude  $\times$  longitude (approx. 1 km) resolution (Fig. 1). Where available, the deltas were digitized based on the corresponding limits defined by aerial photographs, satellite imagery, maps and illustrations in previous studies ( $n = 23$ ). The remaining delta extents ( $n = 17$ ) were defined by the presence of deltaic soils, topography, and the position and upstream limit of distributary channels. Population data for each delta were taken from the 30 arc-second (latitude  $\times$  longitude) resolution Landscan data set (ORNL, 2002).

The delta systems in this study constitute a representative sample of the global population of deltas, spanning a great variety of contributing upland basin areas, climate zones, biomes, coastal receiving waters, levels of economic development, and population densities. In addition, rivers feeding these deltas drain a large portion of the land mass and represent a substantial fraction of the global fluxes of freshwater, fluvial sediment and nutrients destined for the coastal zone (Table 1). River basins draining into these deltas contain 37% of the global population of large reservoirs, 41% of the



**Fig. 1** Example of the digitized delta extent, population estimates and hypsometric relationships used in this study. The Irrawaddy Delta is shown here.

**Table 1** Aggregate contribution of the 40 deltas used in this study with respect to fluvial and geographic attributes, and compared with global totals.

	Sample deltas	Global land mass	% of global total	Mean for 40 deltas	Range
Area (million km <sup>2</sup> )	0.580	133	0.43	0.014	$6.7 \times 10^{-5}$ –0.11
Area of upstream basins (million km <sup>2</sup> )	41	133	30	1.02	0.0384–6.72
2002 Delta population (millions) <sup>a</sup>	288	6310	4.6	7.05	$1 \times 10^{-6}$ –111
Discharge to coastal zone (km <sup>3</sup> year <sup>-1</sup> ) <sup>b</sup>	17 000	40 000	42	410	0.3–7300
Pre-disturbance sediment flux into coastal zone ( $T \times 10^9$ year <sup>-1</sup> ) <sup>b</sup>	6.8	20	34	171	0.0019–1.2
Number of large reservoirs in basin (>0.5km <sup>3</sup> ) <sup>c</sup>	264	714	37	7	1–40
Reservoir capacity in basin (km <sup>3</sup> ) <sup>c</sup>	2109	5170	41	88	0.55–587
Nitrogen flux from upstream ( $T \times 10^6$ year <sup>-1</sup> ) <sup>d</sup>	16.36	40.07	41	-	$2.49 \times 10^{-4}$ –3.82

<sup>a</sup>From Landscan data (ORNL, 2002).

<sup>b</sup>From Meybeck & Ragu (1996).

<sup>c</sup>From ICOLD (1998).

<sup>d</sup>From Green *et al.* (2004).

global reservoir capacity and have a mean upstream sediment trapping efficiency of 47% (ICOLD 1998; Vörösmarty *et al.*, 2003) showing that many of these basins, cumulatively, have undergone a marked and recent alteration to their water and fluvial sediment discharges.

### Estimating effective sea-level rise

We estimate ESLR by examining the relationship between fluvial sediment input, the natural rate of delta subsidence, accelerated subsidence, and the contemporary rates of eustatic sea-level rise. The methodology assumes uniform eustatic sea-level rise and a uniform rate of subsidence and sediment accretion across the extent of each individual delta. Although not universal, these assumptions should not detract from the overall conclusions of this study.

We define: (a) *natural conditions* as a setting in which human impacts are considered minimal, (b) a *contemporary baseline* as present-day sea-level conditions taking into account accelerated eustatic sea-level rise, accelerated subsidence and sediment trapping in upstream reservoirs, and (c) *future conditions* as *contemporary baseline conditions* extrapolated for each delta over the period 2000–2050. Details of the methodology used for estimating each component of equations (1) and (2) that follow and a validation of results can be found in Ericson *et al.* (2006).

The purpose of depicting the *natural conditions* is to have a reference upon which to compare the *contemporary baseline* to determine which sources of change are dominant in each delta. This method assumes that, under *natural conditions*, deltas are in equilibrium and that the ESLR on net is zero. Natural deltaic subsidence and eustatic

sea-level rise are offset by the accretion of fluvial sediment and organic deposition (Sanchez-Arcilla *et al.*, 1998; Milliman *et al.*, 1989; Reed, 2002). The net ESLR ( $N_{\text{eslr}}$ ) under *natural conditions* is calculated as:

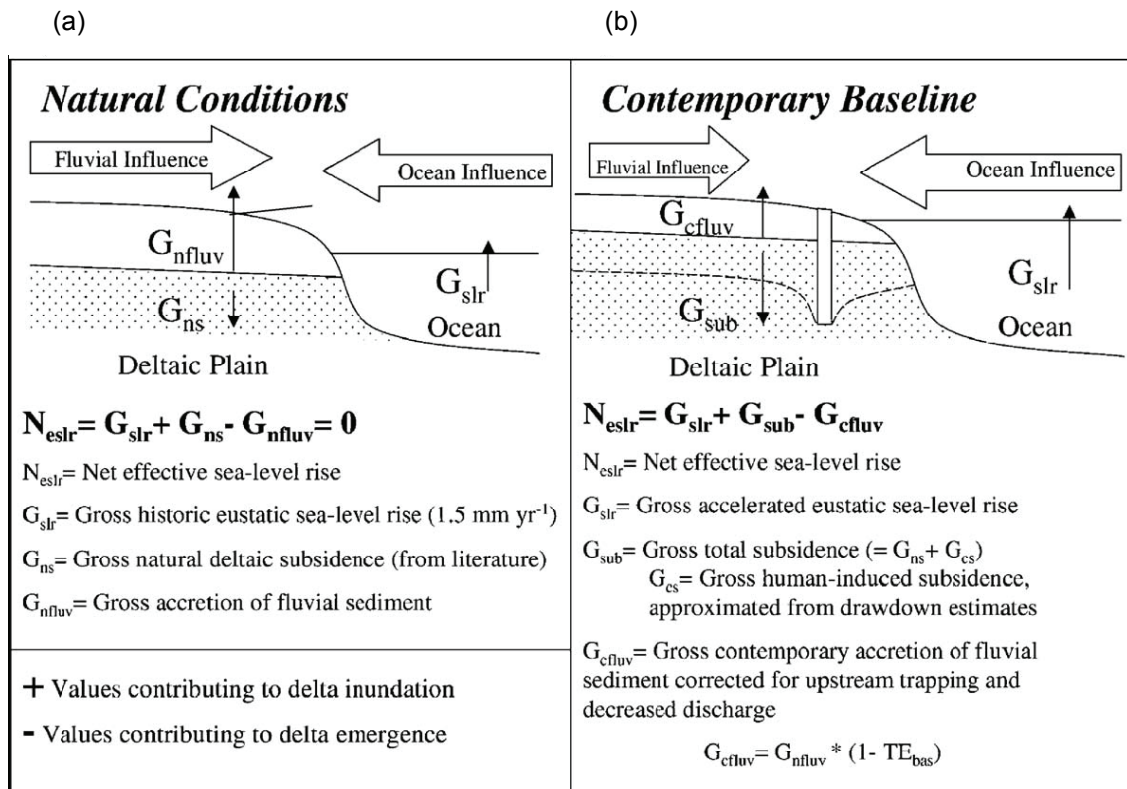
$$N_{\text{eslr}} = G_{\text{slr}} + G_{\text{ns}} - G_{\text{nfluv}} = 0 \quad (1)$$

where symbols are defined in Fig. 2. Each term in equation (1) is positive whenever it contributes to an apparent increase in sea level relative to the delta.

Under the *contemporary baseline* shaped by anthropogenic forcings, changes to the fluvial sediment supply, groundwater and hydrocarbon extraction inside deltas, and any increase in the rate of eustatic sea-level rise, combine in unique ways to determine net ESLR in each delta. Net ESLR under current anthropogenic conditions is thus equal to the sum of change in the rate of fluvial accretion, the increase in total deltaic subsidence, and the rate of eustatic sea-level rise. We define the net ESLR under the *contemporary baseline condition* as:

$$N_{\text{eslr}} = G_{\text{slr}} + G_{\text{sub}} - G_{\text{cfluv}} \quad (2)$$

where symbols are again indicated as in Fig. 2.



**Fig. 2** Schematic of the calculation of effective sea-level rise (ESLR) for individual deltas under: (a) *natural* and (b) *contemporary baseline* conditions. Under *natural conditions* we assume that fluvial sediment accretion and organic deposition offset natural deltaic subsidence and eustatic sea-level rise, resulting in no net ESLR. The ESLR under the *contemporary conditions* is a function of any increase in the rate of eustatic sea-level, changes to fluvial sediment supply and accelerated subsidence in the delta.

**Table 2(a)** Regional distribution of ESLR estimates for deltas, upstream basin sediment trapping efficiency, and accelerated subsidence under baseline conditions.

	<i>n</i>	Mean ESLR (mm year <sup>-1</sup> )	Mean TE (%)	Mean accelerated subsidence (mm year <sup>-1</sup> )
Asia <sup>a</sup>	14	4.6	53.2	2.1
North America <sup>b</sup>	6	4.5	75.1	1.4
South America	5	3.5	66.4	0.3
Europe <sup>c</sup>	6	2.6	51.8	0.1
Africa	7	4.4	75.9	0.5
Oceania <sup>d</sup>	2	1.0	0.0	0.5
Total	40	3.9	57.9	1.1

**Table 2(b)** Regional distribution of the dominant factor in ESLR under *contemporary baseline conditions* for the 40 deltas in this study.

	<i>n</i>	Dominant factor in ESLR		
		Sediment trapping	Accelerated subsidence	Eustatic sea-level rise
Asia	14	8	3	3
North America	6	4	1	1
South America	5	4	1	0
Europe	6	4	2	0
Africa	7	7	0	0
Oceania	2	0	1	1
Total	40	27	8	5

<sup>a</sup> Asia is defined as including the Middle East and Turkey.

<sup>b</sup> North America includes Mexico and Central America.

<sup>c</sup> The eastern border of Europe is defined as Russia's western border.

<sup>d</sup> Oceania includes Australia, New Zealand and Indonesia.

## RESULTS

### Contemporary baseline ESLR condition

Constructing a *contemporary baseline* for ESLR enables us to assess the present-day importance of each major factor contributing to deltaic sea-level rise. The global distribution of ESLR for the *contemporary baseline* ranges from 0.5 to 12.5 mm year<sup>-1</sup> with a mean value of 3.9 mm year<sup>-1</sup> and a median of 4.0 mm year<sup>-1</sup>. Among the highest ESLR estimates are for deltas in south Asia, which tend to be densely populated, agriculturally active and have strongly regulated upland basins. Table 2(a) summarizes the characteristics of ESLR estimates for the sample deltas by continent.

### Dominant sources of present-day ESLR

We define the dominant factor in the *contemporary baseline* ESLR estimate for each delta as the deviation from *natural conditions* that results in the largest proportional contribution to the computed total contemporary ESLR (Table 2(b); Fig. 3). The loss of fluvial sediment resulting from trapping in reservoirs and flow diversion is the



**Fig. 3** Dominant factor determining the estimate of baseline ESLR for each of the 40 deltas. Sediment trapping is the dominant factor for 27 deltas, eustatic sea-level rise is most important for eight deltas and accelerated subsidence predominates in five deltas. This assessment identifies the major factor at play under *contemporary baseline conditions*.

**Table 3** Estimated delta population at risk under *future conditions*, that is, *contemporary baseline conditions* extended from 2000 to 2050. The percentage of population at risk and area potentially lost relate to the total population and area of deltas considered in this study for each continent.

	Total delta population at risk (1000s)	% Delta population at risk	% Delta area potentially lost
Asia	6 570	2.0	3.7
North America	512	6.8	9.7
South America	111	1.5	5.5
Europe	51.7	2.1	4.0
Africa	1 400	1.5	2.5
Oceania	64	6.9	5.5
Total	8 710	2.0	4.9

dominant factor in ESLR for a majority ( $n = 27$ ) of the sample deltas (Table 2(b)). This result is in agreement with recent studies that recognize the influence of reservoir construction on fluvial sediment flux to the coastal zone (Walling & Fang, 2003; Vörösmarty *et al.*, 2003) and is discussed in the Conclusions.

### Estimates of ESLR to year 2050

The *contemporary baseline* ESLR estimates were extrapolated from 2000 to 2050 to estimate potential vulnerability to sea-level incursion into deltas. The populations affected and land areas lost (Table 3) were determined from population–elevation and area–elevation distribution curves for individual deltas as given in Fig. 1. Future populations were estimated from national population growth statistics to 2050 and applied spatially according to the Landscan population data distributions (ORNL, 2002; PRB, 2004). It should be noted that these estimates do not consider human response to rising waters such as abandonment or protection of land with seawalls and embankments.

Moreover, these estimates do not take into account coastal erosion from storm impacts, thus making the estimates conservative.

Total population in the 40 deltas potentially affected by inundation extrapolated from the *contemporary baseline* ESLR by year 2050 is approximately 9 million. Expressed as a percentage of the total population in the 40 sample deltas, those people at risk represent 2% of the full sample with a range from 1.5 to nearly 7% for individual continents. Land area at risk totals about 30 000 km<sup>2</sup> (about 5% of the sample total) with a range for continents from 2.5 to 10%.

## CONCLUSIONS

Using a newly developed geospatial data set of delta attributes, we applied a method to estimate the effective sea-level rise in individual deltas based on fluvial sediment inputs to the deltas, natural rates of delta subsidence, accelerated subsidence resulting from groundwater and hydrocarbon withdrawal, and reported rates of eustatic sea-level rise. The method was applied to a sample of 40 deltas distributed across a wide range of climatic, geomorphologic, and economic development conditions.

The sources of this vulnerability are derived predominantly from human activities on the continental landmass. Our results suggest that decreased fluvial accretion resulting from sediment loss in upstream reservoirs and flow diversion is the primary factor defining ESLR in nearly 70% of the 40 deltas studied here. Sediment trapping by reservoirs has been identified as a significant impediment to sediment delivery to the coastal zone (Vörösmarty *et al.*, 2003; Syvitski *et al.*, 2005); a recent study of sediment flux data for 145 rivers indicates that of the approximately 50% showing statistically significant trends, the majority have decreasing sediment loads (Walling & Fang, 2003). Our results also support observations about the dominant factor in deltaic land loss in individual deltas including the Indus, Nile, Ebro, Volta and Niger deltas (Collins & Evans, 1986; Stanley & Warne, 1998; Sanchez-Arcilla *et al.*, 1998; McManus, 2002).

Under baseline conditions, estimates of ESLR rates for the sample of 40 deltas range from 0.5 to 12.5 mm year<sup>-1</sup>, much higher than the 1.5–2 mm year<sup>-1</sup> eustatic sea-level rise of the 20th century (Miller & Douglas, 2004). We estimate that if the rate of ESLR should persist at current levels and no mitigative responses are undertaken, 4.9% of the deltaic areas considered by this study and 8.7 million people could potentially be affected by coastal inundation by 2050.

Such aggregate numbers mask important regional and individual delta effects. Nearly 75% of the total population impacted is in the Asian deltas, reflecting both the bias towards these deltas in our study ( $n = 14$ ) and their high populations. The Bengal delta has by far the largest potential impact on humans (3.4 million affected), but this is only 1.8% of the estimated Bengal delta population in 2050. Similarly, the average percentage of the total delta population affected across Asian deltas is relatively low (2.0%) in comparison with percentages in some other regions. North American deltas show nearly the highest percentage (6.8%) of its deltaic populations experiencing potential inundation as well as the highest percentage of delta area impacted (9.7%). The ranges for the percentage of the total delta population at risk and percentage of total delta area lost by continent are 1.5–6.9% and 2.5–9.7%, respectively.

Loss of fluvial sediment input has already resulted in observed land loss and coastal erosion in many deltas, and these impacts will continue to occur as the demand for water resources increases in many parts of the world. Of the approximately 1000 large dams (>15 m height) under construction in 2000, 78% are located in Asia, 12% in Europe (predominately Eastern) and 5% in Africa (IWPDC, 2000), where there are high population densities and high levels of potential vulnerability. The concentration of planned reservoirs indicates that in some areas, particularly Asia, fluvial sediment trapping will continue to be an issue for the foreseeable future.

The recent emphasis on climate-related sea-level rise, which we find to be a relatively minor influence on the overall condition of deltaic systems, suggests that we are today poorly prepared to respond to the broad array of other critical determinants of coastal system stability well into the future. Deltas are particularly vulnerable to the combined effects of landward and seaward-derived forces and future studies must combine terrestrial and coastal ocean perspectives. Greater awareness of potential threats to such systems is a precursor to the design of responses that maximize the protection of life, infrastructure, and economic development.

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