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Divergent options to cope with vulnerability in subsiding deltas

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Abstract Net subsidence of most major deltas in the world and related vulnerability are thought to be increasing, and this is often linked causally to human activities. This paper examines this causality against a range of co-varying factors. We do so with a principal component analysis of co-variability of a range of geophysical and socio-economical indicators of 33 deltas mainly derived from the DIVA tool. Land potentially lost and people at risk of flooding are our indicators of vulnerability. The former correlated positively with maximum surge height and negatively with net sea level rise. The latter correlated positively with delta area, average river discharge, and maximum surge and negatively with net uplift (or subsidence). Thus, variation in societal vulnerability across deltas depends on short-term, instantaneous risks linked to lowland area, river discharge and storm surges rather than on longer-term, slow, net sea level rise. Delta management should focus on precautionary spatial planning, and on maintenance or restoration of historical sediment delivery and accretion rates. Especially larger deltas with high population densities combine a high risk with the potential to accommodate flood water and mitigate flooding risks. The deltas of the Yangtze-Kiang and Ganges-Brahmaputra share these characteristics. Here space should allow engineering of flood retention, sedimentation and diversion channels as well as refuges and safe economic hotspots. At the other end, in deltas with a high population density and limited space, like the Chao Praya, means for adaptation must be sought outside the delta proper. In deltas with low population densities, such as the Lena, Yukon or Fly, natural delta dynamics can prevail.

1 Introduction

Most modern deltas will not keep up with current and projected sea level rise, as Ericson et al. (2006) and Syvitski et al. (2009) have demonstrated. Most probably, global sea level rise

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will continue at present rates or accelerate (Bindoff et al. 2007). Hence, prevailing net subsidence implies that valuable land and associated economic assets will drown over the coming decades, notably in vulnerable deltas (Syvitski et al. 2009). However, net subsidence does not necessarily imply an increase in vulnerability, quantified here as land lost and people at risk (Nicholls 2004; McFadden et al. 2007; Marchand 2009; defined in Table 1). Vulnerability seen this way has a geophysical and a socio-economic component. The former is related to coastal geomorphology, and the latter to population density, accumulated wealth, societal institutions and hazard preparedness. Our aim is to analyse how both geophysical and socio-economic elements contribute to the compound vulnerability of deltas, as foci of socio-economic activity (Doll et al. 2006; Syvitski et al. 2009). For this purpose we analysed co-variability, resolution and span of a range of geophysical and socio-economical vulnerability indicators of 33 major deltas derived from two comparable global databases, the World Delta Database (WDD) and the DIVA tool (Hart and Coleman 2004; Hinkel and Klein 2009). This breakdown of vulnerability into underlying components will be helpful to identify viable adaptation policy options.

2 Material and methods

The DIVA tool (Vafeidis et al. 2008; Hinkel and Klein 2009; Hinkel et al. 2010) was obtained from Jochen Hinkel, maintaining the tool for the DINAS-COAST consortium. DIVA combines a global database of the world's coast broken down in coastal segments of variable length with a world climate and socio-economic model. We extracted from DIVA those coastal segments that have a delta. DIVA allows scenario analysis with pre-incorporated SRES- or custom-made scenarios. A scenario run in DIVA generates stepwise annual worldwide climate, demographic and economic output for a user-defined period up to 2100, disaggregated to coastline segments from regional and national estimates (Hinkel and Klein 2009). Here we only present outcomes for 2000 as 'current', and for the SRES scenarios A2 and B1 for 2100, because these span the full width in present model outcomes (cf Lorenzoni et al. 2000). DIVA variables included in the analysis are presented in Table 1. The WDD was obtained from the website maintained by George Hart and Jim Coleman at http://www.geol.lsu.edu/WDD/. The latter database provided mainly geophysical data that partly overlapped with DIVA, hence we only used delta area from the WDD. For the purpose of verification, we compared our DIVA and WDD data with those of Ericson et al. (2006), Overeem and Syvtski (2009), and Syvitski et al. (2009). Our data did correlate quite well with those of the other two sources (r^2 values range between 0.44 and 0.75, all $p<0.05$; Supplementary Material S1), although our delta area was substantially larger (~4x) than that of Syvitski et al. (2009), probably due to a restricted upper elevation limit used by the latter. Next, we performed a multivariate analysis on the final table with 21 variables for 33 deltas. We analysed covariance patterns with a principal components analysis (PCA) based on the correlation matrix and without any variance-maximizing rotation. Subsequently we analysed dependence of our two main vulnerability indicators, land lost and people at risk of being flooded, to possible forcing factors in the full matrix using multiple regression.

3 Results and discussion

Average river discharge, delta area, subsidence and the maximum storm surge height co-varied distinctly with the first principal component, and in a direction orthogonal to net sea level rise,

Table 1 Variables extracted from the DIVA tool for 33 deltas* that have been used in the PCA. Delta area was extracted from the World Delta Database (see text)

variable name	Description	abbreviation in DIVA	Spatial scale in DIVA**
area under 2m AMSL	Area in the coastal zone with elevation below 2 m AMSL derived from GTOPO30 digital elevation dataset	Areaunder1+2	coastline segment
coastal slope	Slope of land up to 3 m above max surge level (degrees).	Slope	coastline segment
subsidence	Net subsidence (mm yr^{-1}), correcting for isostatic uplift.	Upsub	coastline segment
wave climate	wave climate based on LOICZ classes: 0 no waves permanent sea ice; 1 0–2.5 m, 2: 2.5–3.5 m, 3 3.5–5 m, 4 5–6.5 m, 5>6.5 m	Wavclim	coastline segment
coastal population density	Population density on the coast, that is in a zone of 2.5 km behind the coastal segment (N km^{-2}). DIVA applies the GWP2 data set, normalised to 1995	Copopd	coastline segment
GDPpc	Per capita gross domestic product, in 1995 US$	GDPpc	admin unit
dike height	Sea dike height, calculated height of a dike on a segment (m)	Sdikehght	coastline segment
maximum surge height	Maxsurge=1 in 1000 surge height+3 (m), including high water level, above mean sea level	Maxsurge	coastline segment
land below 1/1000 surge height in 2000, for A2 and B1	Vulnerability indicator: Land lost Potential floodplain, land area below the one in one thousand flood level, ignoring sea dikes (km^2), estimated for 2000 and 2100 using scenarios A2 and B1; interpreted here as land potentially lost. ***	Potfloodplain	admin unit
people potentially flooded	People in the flood hazard zone: people living below the 1000 year surge (ignoring sea defences, in 2000, and in 2100 for A2 and B1). Aggregation rule, sum of coastline segments within administrative unit. (1000s of people)	People potentially flooded, Ppf	admin unit
people at risk in 2100, for A2 and B1	Vulnerability indicator: People at risk of flooding. People actually at risk of being flooded : average number of people flooded per year by storm surge allowing for the effect of flood defences. Aggregated as sum of coastline segments within administrative unit (x1000, yr^{-1}).	Paf	admin unit
relative sea level rise, for A2 and B1	Mean change in relative sea level compared to the reference year (1995) weighted by segment length. It considers (1) human-induced	Rslr	admin unit

Table 1 (continued)

variable name	Description	abbreviation in DIVA	Spatial scale in DIVA**
	climate change under the selected scenario, (2) uplift/subsidence due to glacial-isostatic adjustment and (3) natural subsidence of deltaic areas (m); in 2100, for A2 and B1		
total area of natural wetlands	Sum of area of all coastal types of wetlands in an administrative unit (km^2)	Sumnatural-wetlands	admin unit
river discharge	Mean discharge reported at a station nearest to the sea (m^3/s)	Avgdisch	river segment

*these were: Burdekin, Chao Phraya, Danube, Dneiper, Ebro, Fly, Ganges-Brahmaputra, Godavari, Huang He (Yellow), Indus, Irrawaddy, Krishna, Lena, MacKenzie, Magdalena, Mahakam, Mahanadi, Mangoky, Mekong, Mississippi, Niger, Nile, Orinoco, Parana, Pechora, Po, Red, Sao Francisco, Senegal, Shatt el Arab, Yangtze-Kiang, Yukon, and Zambezi

** The DIVA tool applies the coastal segment as smallest unit. Coastal segments have a variable length and some have a river attached with additional information. Part of the data in the database are aggregated at the scale of the first administrative unit under the nation state, other data were available per nation only as is specified in DIVA

*** DIVA also calculates land flooded with a 1 in 100 and 1 in 10 year return period. These three variables are significantly correlated. We therefore only present the most extreme of the three

or coastal slope (Fig. 1, Table 2; the latter not significantly). Land lost and people at risk of flooding, our proxies of vulnerability, correlated with the former four rather than the latter two variables. Hence, variation in vulnerability across deltas appeared primarily a function of storm surge height, river discharge and spatial extent of the delta or adjacent lowland area, rather than of longer-term, slow, net sea level rise (Fig. 1). Overall, future maximum storm surges should be expected to increase with sea level rise (e.g. Strauss et al. 2012), but this appears to have little influence on the variation in vulnerability among deltas in our data set. Variability among deltas was much higher in the area of the coastal zone under 2 m and in the land potentially lost (coefficient of variation 2.2), as well as in population density (cv=1.7), than in relative sea level rise (cv=0.2). The same sea level rise will have profoundly different effects in different deltas, depending on coastal morphology and population density. Similarly, Tebaldi et al. (2012) observed considerable spatial variability in the response of flood return periods along the coasts of the USA. Individual scatter plots (Fig. 2) support the pattern of correlations among variables in the PCA depicted in Fig. 1: people at risk of flooding correlated strongly with PC1, delta area, and coastal population density. The latter correlated significantly, but less strongly with PC2 (Fig. 2a, b, c). Maximum surge height correlated significantly with land lost (Table 3). Although the individual bivariate regression had a low r^2 (Fig. 2d), multiple regression models explained more (Table 3).

Current vulnerability predicted future vulnerability quite well (Fig. 2e), Also the two SRES scenarios show wide divergence, as A2 will lead to about twice as much land potentially flooded as B1, and B1 is comparable to the current situation (Fig. 2e). The Yangtze-Kiang is a distinct outlier under B1. Accounting for the presence of sea defences appears to increase the variation in vulnerability among deltas: compare the spread among scenarios in people potentially flooded with that in people at risk (Fig. 1). This does

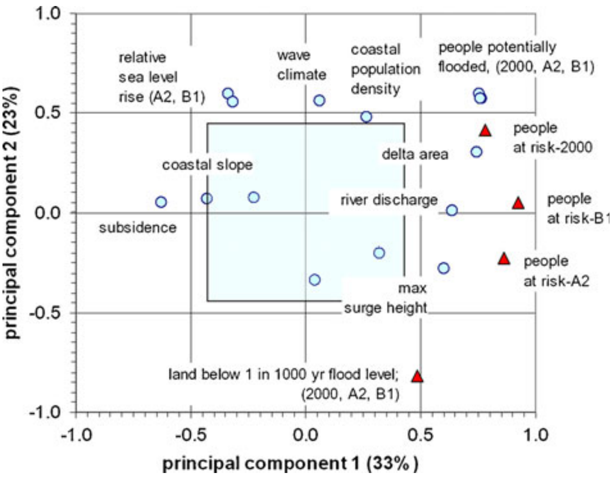

Fig. 1 Co-variability among geophysical and socio-economic vulnerability indicators of 33 deltas. Displayed are correlations of original variables with the first and second principal component of a PCA (cf Table 2 and Fig. 2a, b). Variables reflect current (year 2000) coastal conditions and model runs with contrasting SRES-scenarios A2 and B1 for the year 2100. The semi-transparent frame shades correlations below 0.45, corresponding to a level of significance for pairwise regressions of 0.01. Red triangles are used for the three vulnerability indicators

underline the importance of the socio-economic component: under A2 more people are flooded (Fig. 2e) and this variable also covaries more closely with surge height under A2 (Fig. 1).

The linearity with ‘current’ is striking. The variability among deltas appears to be maintained despite substantial differences in economic and population development for different regions in the two scenarios. So an increased SLR with A2 is important in

Table 2 Correlation of socio-economic and geophysical variables with the first three principal components of a PCA for 33 deltas. Also presented is the percentage of the total variability explained by each principal component. In bold: correlations above 0.45 (p<0.01). Only the first three PCs are presented, these explain more than 10% of the variance

Principal component	1	2	3
percent of variance explained	32	23	12
subsidence	**-0.63**	-0.05	**0.53**
coastal slope	-0.43	-0.07	-0.22
relative sea level rise in 2100 - A2	-0.34	**0.59**	**0.63**
relative sea level rise in 2100 - B1	-0.31	**0.55**	**0.65**
total area of natural wetlands	-0.23	0.07	**0.72**
wave climate	-0.06	**0.56**	0.01
area under 2m AMSL	0.04	-0.34	**0.59**
coastal population density	0.27	**0.48**	-0.09
dike height	0.32	-0.20	0.30
river discharge	**0.64**	0.01	0.45
maximum surge height	**0.60**	-0.28	0.00
delta area	**0.74**	0.30	0.20
land below 1/1000 surge height in 2000	**0.49**	**-0.82**	0.19
land below 1/1000 surge height in 2100 - A2	**0.48**	**-0.82**	0.20
land below 1/1000 surge height in 2100 - B1	**0.48**	**-0.82**	0.19
people potentially flooded in 2000	**0.77**	**0.57**	-0.04
people potentially flooded in 2100 - A2	**0.75**	**0.59**	-0.03
people potentially flooded in 2100 - B1	**0.66**	**0.70**	-0.02
people at risk in 2000	**0.78**	0.41	-0.07
people at risk in 2100 - A2	**0.86**	0.23	0.11
people at risk in 2100 - B1	**0.92**	0.05	0.03

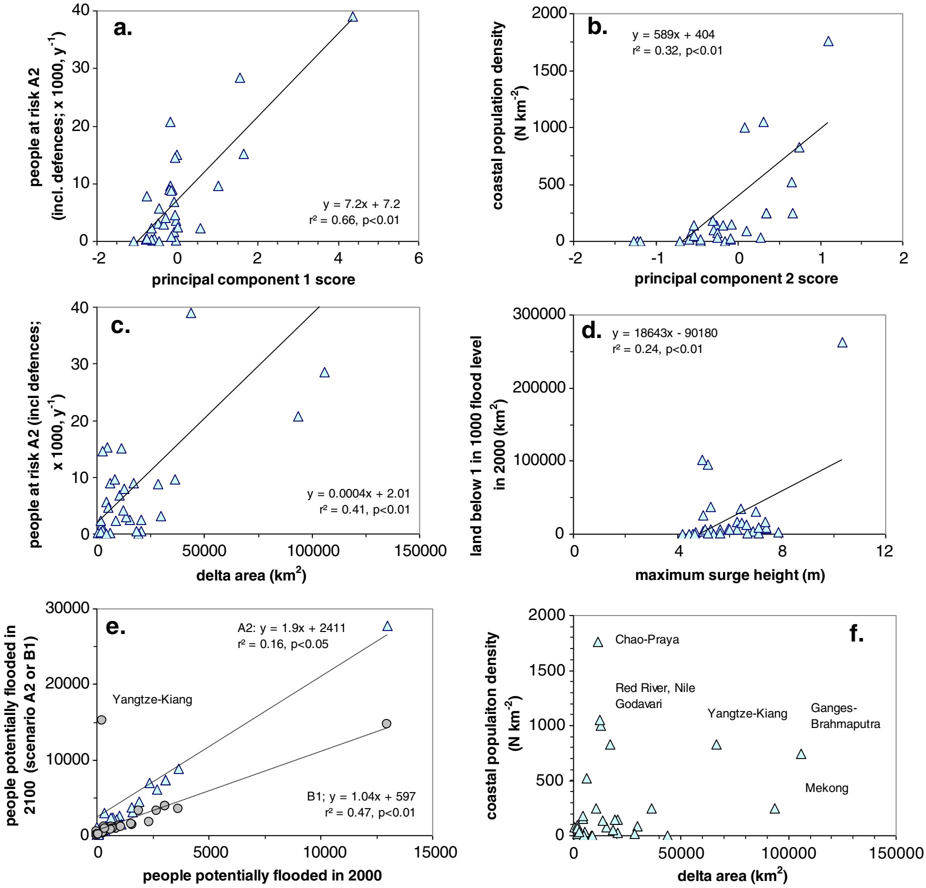

Fig. 2 Scatter plots of some of the covariates for the 33 deltas included in the PCA. (**a**) people actually at risk of flooding under the A2 scenario versus the scores of principal component 1; (**b**) coastal population density versus the score of principal component 2; (**c**) people at risk of flooding under A2 versus delta area; (**d**) land below the 1 in 1000 flood level versus maximum surge height; (**e**) people potentially flooded in the future (A2: triangles, B1: circles) versus the 'current' estimates; and (f) coastal population density versus delta area

increasing overall global vulnerability, but the pattern of differences among deltas appears quite robust. It should be noted that we have not implemented a low probability extremely high sea level rise in our DIVA runs, but adhered to the commonly applied SRES scenarios. For A2 the mean sea level rise until 2100 across our deltas was 53±0.4 cm.

A scatter plot of all 33 included deltas for population density against delta area (Fig. 2f) suggests that the Asian deltas Mekong, Yangtze-Kiang, Ganges-Brahmaputra and Chao Praya are the main outliers. Larger deltas with high population densities combine a high risk with the potential to accommodate flood water and mitigate flooding risks. The deltas of the Yangtze-Kiang and Ganges-Brahmaputra share these characteristics (Fig. 2f) and are also ranked as deltas at risk by Syvitski et al. (2009). However, particularly here space should allow for the engineering of flood retention, sedimentation and diversion channels as well as refuges and safe economic hotspots. At the other end, in deltas with a high population density and limited space, like the Chao Praya (Fig. 2f), means for adaptation must be sought

Table 3 Multiple regressions of three vulnerability indicators and potentially forcing, independent variables. Only the significant, independent variables are presented. Full model contained: delta area, average discharge, coastal slope, net subsidence, max surge, wave climate, coastal population density, GDPpc and relative sea level rise in 2100, given the A2 scenario (cf Table 1)

Vulnerability indicator	Significant independent variables (standardized beta, p, r^2)	
	Full model entered	Stepwise approach
Land below the 1/1000 surge level in 2000, potential floodplain	Max surge (0.48, 0.007,-)	Max surge (0.61, <0.001,0.26)
	Wave climate (-0.31, 0.057*; 0.61)	Wave climate (-0.35, 0.012; 040)
		GDPpc (0.35, 0.013, 0.52)
People at risk of being flooded, in 2000, allowing for flood defences	Delta area (0.87, <0.001, -)	Delta area (0.85, <0.001, 0.71)
	Sea level rise (-0.32, 0.07*, 0.78)	
People at risk of being flooded in 2100, A2	Delta area (0.38, 0.058, -)	Delta area (0.64, <0.001, 0.41)
	Coastal population density (0.32, 0.041, 0.61)	

* These two variables have a $p > 0.05$, hence should not be considered to explain a significant proportion of the variation in the dependent

outside the delta proper. In deltas with low population densities, such as the Lena, Yukon or Fly, natural delta dynamics can prevail.

We carried out multiple regressions to separate the geophysical and socio-economic component of vulnerability (Table 3). Land that is vulnerable to present and future flooding varies most strongly with the maximum surge height, a geophysical indicator. Wave climate was also significant, but less important. Stepwise regression modelling adds GDPpc (per capita gross domestic product) as another indicator, implying the accumulation of wealth in large coastal plains as a separate independent factor, but this variable adds only little explanatory power. The total number of people at risk of being flooded is a straightforward function of deltaic area and coastal population density, together explaining 61% of the variance. Deltaic area explains 41%; hence this geophysical aspect explains most of the variability in vulnerability.

Syvitski et al. (2009) claimed that “It remains alarming how often deltas flood, whether from land or from sea, and the trends seem to be worsening.” Instead, we argue that one should rather favour continued, frequent or previous flooding regimes where possible, since this flooding will at least deliver some of the sediment needed to counter net subsidence (Syvitski et al. 2003; Walling 2006). Also, the empirical support for a “worsening trend” is equivocal (Kundzewicz et al. 2005; Bouwer et al. 2008; Bouwer 2011): rather than increased flood frequencies it is the increased human population (Small and Nicholls 2003) and the accumulation of wealth that lead to increased disaster loss and vulnerability.

In general, we conclude from the observed pattern that variation in societal vulnerability in deltas depends rather on short-term and local risks linked to lowland area, peak discharge and storm surges than on longer-term, slow, more large-scale and net sea level rise in deltas. Here we support Nicholls and Cazenave (2010) in their stress on local non-climate-related drivers of vulnerability to net sea level rise. Therefore, the focus of adaptation policy should be on precautionary spatial planning, and on maintenance or restoration of historical sediment delivery to prevent sediment starvation and delta subsidence. At the same time, we recognize that often land degradation in the hinterland has historically provided the sediment to sustain the rapid accretion of deltas (cf Hanson 1990; Lavigne and Gunnell 2006; Thampanya et al. 2006; Walling 2006), whereas the last century witnessed major damming of rivers, which starved deltas (Thampanya et al. 2006; Walling 2006) and reduced sea level rise (Nicholls and Cazenave 2010; Pokhrel et al. 2012). These dams are not easily removed, and it is questionable whether further, up-catchment land degradation is to be favoured to ensure coastal sediment delivery.

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