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Journal

Sustainability Science, 12(3)

ISSN

1862-4065

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Publication Date

2017-05-01

DOI

10.1007/s11625-016-0420-2

Peer reviewed

Sustain Sci
DOI 10.1007/s11625-016-0420-2

SPECIAL FEATURE: CASE REPORT

Sustainable Deltas: Livelihoods, Ecosystem Services, and Policy Implications

Unravelling the association between the impact of natural hazards and household poverty: evidence from the Indian Sundarban delta

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Received: 3 August 2015 / Accepted: 18 December 2016

Abstract Coastal regions have long been settled by humans due to their abundant resources for livelihoods, including agriculture, transportation, and rich biodiversity. However, natural and anthropogenic factors, such as climate change and sea-level rise, and land subsidence, population pressure, developmental activities, pose threats to coastal sustainability. Natural hazards, such as fluvial or coastal floods, impact poorer and more vulnerable communities greater than more affluent communities. Quantitative assessments of how natural hazards affect vulnerable communities in deltaic regions are still limited, hampering the design of effective management strategies to increase household and community resilience. Drawing from Driving Forces–Pressure–State–Impact–Response (DPSIR), we quantify the associations between household poverty and the likelihood of material and human loss following a natural hazard using new survey data from 783 households within Indian Sundarban Delta community. The results suggest that the poorest households are significantly more likely to endure material and human losses following a natural hazard and repeated losses of livelihood make them more vulnerable to future risk. The results further suggest that salinization, tidal surge, erosion, and household location are also significant predictors of economic and human losses. Given the current and projected impact of climate change and importance of delta regions as the world's food baskets, poverty reduction and increase societal resilience should be a primary pathway to strengthen the resilience of the poorest populations inhabiting deltas.

Keywords Natural hazards · Livelihoods · Climate change · Indian Sundarban delta · Sustainable delta · Sustainable development

Handled by Fabrice Renaud, United Nations University Institute for Environment and Human Security Bonn, Germany.

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Introduction

Maritime and lacustrine delta regions are home to over half a billion people and constitute global food baskets (Foufoula-Georgiou et al. 2011; Szabo et al. 2015a), yet at the same time, they are highly vulnerable to the impacts of environmental and climate change, including natural hazards (Szabo et al. 2015a; Tessler at al. 2015). While there is existing evidence regarding the consequences of natural hazards (Blaikie et al. 2014; Barbier 2014; IPCC 2007), quantitative assessments of the associations between household poverty and the human and material loss resulting from natural hazards are still limited. Some evidence suggests that social factors at a range of scales, from differences in local housing stocks to regional governance structures, can affect the material and human losses that stem from natural hazard events (World Bank 2013).

In low-income countries, adverse events and hazards can be a drain on the economy and result in welfare losses (Mazumdar et al. 2014; Pelling and Uitto 2001; Dercon 2004; IFRCRCS 2010). Economic losses associated

Published online: 27 February 2017

with natural hazards were estimated at approximately US $165 billion per year during the last 10 years (World Bank 2014b), and natural hazards caused approximately US $116 billion in financial losses in 2013 (Guha-Sapir et al. 2014). In the US, economically poor people have been found to be more vulnerable to natural hazard events due to less preparedness and lower ability to recover from livelihood losses (Fothergill and Peek 2004). Poor households often have limited access to income, water, and sanitation. Furthermore, many poor live in inadequately constructed houses, which make them more sensitive to extreme weather conditions and other direct and indirect impacts of natural hazards (Lal et al. 2009; Brouwer et al. 2007).

The overall risk to societies or individuals from natural hazards reflects the combination of the probability of a hazardous event occurring and the magnitude of negative consequences as a result of that event (UNISDR 2007). Vulnerability describes the losses that manifest from the occurrence of a natural hazard. This depends on both potential exposure to hazards and societal resilience which is defined as the ability to resist, absorb, and recover from hazardous effects (UNISDR 2009) with a specific focus on particular places or regions (Kasperson et al. 1995; Cutter et al. 2000). Socio-economic vulnerability is defined as the stress on livelihoods of individuals or collective groups as a result of the impacts of environmental changes (Adger 1999). Higher levels of vulnerability are correlated with higher levels of poverty, weaker social ties between people, and political and cultural seclusion (Chakraborty et al. 2005). Some communities absorb environmental shocks and recover more readily than others because of physical assets, social capital, and political access. Risks from natural hazards are distributed across all levels of economic development; however, wealthy countries have the capacity to reduce the risk of natural hazards through construction of improved infrastructure (e.g., Tessler et al. 2015). At the household level, both short and long-term impacts of natural hazards vary depending on the socio-economic status of the affected community, with the poorer strata of the society tending to carry the major share of the burden in all hazardous consequences (Mazumdar et al. 2014). Unexpected extreme natural events may exhaust household resources and lead to poverty traps (Carter et al. 2007). The World Bank (2000) reported that loss of assets can push poor households into chronic poverty traps as they do not have the necessary income to rebuild houses, replace assets, and cope with negative health outcomes.

Coastal areas are exposed to a variety of natural hazards, such as river flooding, tsunamis, hurricanes, and transmission of marine-related infectious diseases. Worldwide, 850 million people live within 100 km of tropical coastal ecosystems, with an estimated increase 1.4 billion coastal people by 2060 (Neumann et al. 2015; IPCC 2014). An estimated 10 million people experience coastal flooding each year due to storm surges and typhoon landfalls (Mousavi et al. 2011). Deltaic regions, such as the Indian Sundarban Delta (ISD), are also prone to the impacts of environmental change, such as soil salinization and riverbank erosion, which can lead to shifts in occupational patterns and greater food insecurity (Szabo et al. 2015a, b). Around 2.3 million people of ISD were affected by cyclone Sidr in 2007 and cyclone Aila in 2009 (Hazra et al. 2014). The study islands are affected by coastal erosion and cyclonic surge, along with over population and over exploitation of resources.

The present study aims to assess the associations between household poverty and the likelihood of material and human loss following a natural hazard in the islands of the Indian Sundarban Delta (ISD). Previous research suggests that riverbank erosion associated with sea-level rise poses a serious threat to the existence of the islands of the ISD (Raha et al. 2012; Hazra et al. 2010; Hazra 2003). Although earlier studies investigated the impacts of natural hazards on livelihoods in nearby coastal islands of Bangladesh Sundarban Delta and low-elevation deltas in other geographical setup (Hossain et al. 2012; Shamsuddoha and Chowdhury 2007; Fothergill and Peek 2004; Lal et al. 2009), there is limited research examining the connections between vulnerability to natural hazards and poverty in the ISD. Our study aims to fill this gap by examining on how economic poverty affects losses from natural hazards at a household level in the ISD and offer a number of concrete policy recommendations to reduce vulnerability to natural hazards. We conducted our analysis following a conceptual framework based on the Driving Forces–Pressure–State–Impact–Response (DPSIR) concept (EEA 1999). Primary data from household survey within ISD community, conducted in 2012–2013, are analysed using logistic and multinomial regression techniques.

Socio-economic vulnerability and impacts of natural hazards in the Indian Sundarban delta

The Indian Sundarban Delta (ISD) region extends from 21°30′N to 22°40′48″N latitude and from 88°1′48″E to 89°04′48″E longitude. The entire Indian Sundarban is bounded by the estuary of River Hooghly on the west to Ichamati–Raimangal in the east, the Bay of Bengal in south, and the Dampier Hodges line in the north (Das 2006). The area is a low, flat, alluvial plain covered with mangrove swamps and marshes, intersected by a large number of tidal rivers, estuaries, and creeks. The drainage network and dynamic flow patterns of tidal water, along with the erosion accretion of land, have built up a complex geomorphology in this area (Das 2006). Both climatic and non-climatic events adversely affect the livelihoods of the people of the Indian Sundarban Delta (ISD). Land loss due to submergence and increases in soil salinity and land fragmentation all make life of the islanders of ISD difficult. The ISD remains one of the most under-developed places in India, with 34% of the 4.6 million people who inhabit the islands living below the poverty line (Hazra et al. 2014). About 89% of the total population of the region is dependent on mono crop (Aman paddy) cultivation (Hazra et al. 2002).

Climate change, induced sea-level rise, changing rainfall patterns, and changes in the frequency and intensity of extreme weather events have had significant impacts on the islanders of ISD (WWF 2010). Cyclonic storm surges can damage embankments and lead to saline water intrusion into agricultural fields (Chand et al. 2012; Hazra et al. 2014). As a consequence of Cyclone Aila in 2009, rice production was reduced to 32–40 quintal per 1.6 hectares from 64 to 80 quintal per 1.6 hectares produced before the event (Debnath 2013). The worst affected was the economically poorer section, with an economic loss of US $2253.12 million, with around 200,000 poor houses damaged by the event (Hazra et al. 2014).

Conceptual framework

The conceptual framework in this study is based on the Driving Forces–Pressure–State–Impact–Response (DPSIR) approach. The DPSIR framework helps illustrate a key relationship between households' socio-economic vulnerability and the likelihood of loss following an extreme event or natural hazard. Natural hazards put a disproportionate amount pressure on the state of poor households, resulting in livelihood loss and material poverty. The resulting impact leads to policy formulation in response. In the late 1990s, the DPSIR framework emerged from the previous Pressure–State–Response (PSR) framework established by the Organization for Economic Cooperation and Development (OECD) (1993, 1998). The PSR framework considered only anthropogenic impacts on the environment, putting natural variability aside (Carr et al. 2007). To overcome this problem, the UN Commission on Sustainable Development (UNCSD 1997) attempted to formulate a new Driving Forces–State–Response (DSR) framework, which includes not only the social, political, economic, and demographic pressures in the PSR model, but also pressures that result from the natural system. While the former PSR model only focused on the anthropogenic pressure and response, the DPSIR model is more comprehensive and incorporates natural driving forces (Bowen and Riley 2003; Poveda and Lipsett 2011). Environmental management studies often adopt a DPSIR-based model to analyse factors behind the problem being addressed for specific policy options (Jorge et al. 2002).

The suggested conceptual framework (Fig. 1) draws from the DPSIR framework, specifically focusing on deltaic environments. Natural hazards influence the economic state of a society in terms of livelihood losses. Thus, these hazards are creating pressure on the poorer community. Based on the impacts generated by these hazards, sustainable development policies are then needed to help respond to, mitigate, and perhaps even prevent such impacts.

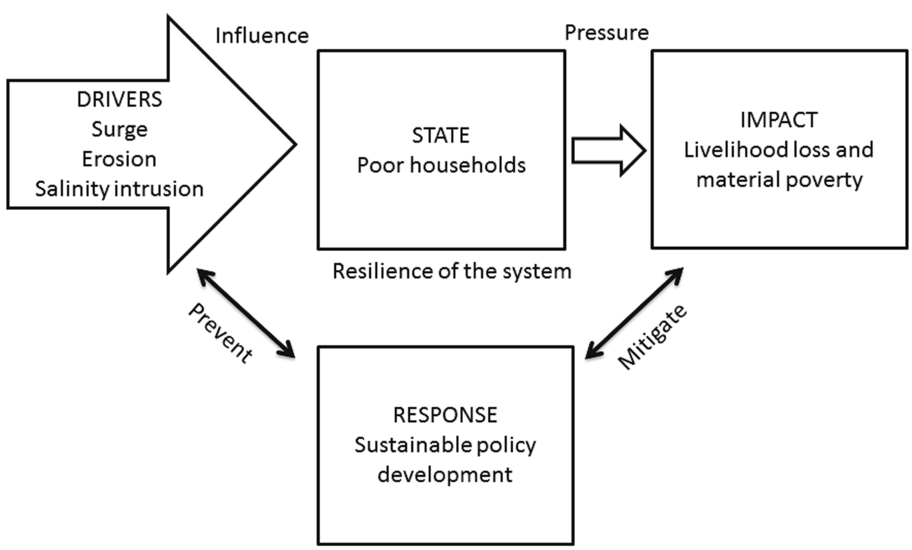

Fig. 1 Conceptual framework adapted from the Driving Forces–Pressure–State–Impact–Response approach

Analytical approaches

Study area

The study area encompasses three islands (Sagar, Ghoramara, and Mousani), all located on the western fringe of the ISD. Sagar Island (Fig. 2), the largest in ISD, is situated at the estuary of the river Hooghly on the southwest of the ISD. Administratively, Sagar Island is classified as a "Block", a collection of mouzas or villages, and is the most populous ISD island with a population of approximately 200,000 people (Census, 2011). It is bounded by the Hooghly River to the north and west, the Muriganga River to the east, and the Bay of Bengal to the south. Overall, there are 42 villages on Sagar Island.

The Ganga–Bramhaputra–Meghna river system carries sediment load comprised of sand, silt, and clay, and drains through an alluvial plain on its course to the Bay of Bengal, while at the mouth, tidal forces obstruct sediment delivery to the sea, resulting in sediment back-load and deposition along the course, thus helping island formation (Das 2006). The drainage network and dynamic flow pattern of the tidal water, along with erosion and land accretion, make the geomorphological setup of the area very complex. The study area is characterised by a flat alluvial plain with a ground elevation varying from 2.10 to 2.75 m above mean sea level (Purkait 2009). Sagar Island enjoys better infrastructural facilities than other two study islands, including an improved road network, flood shelters, and a rural hospital (HDR 2009).

Ghoramara Island, located to the north of Sagar Island, has experienced a high rate of erosion since the 1970s, which has led to massive out-migration of inhabitants to other parts of Sundarban, including Sagar. This island is located within the Hooghly estuary in the western part of ISD. Ghoramara Island covers an area of 4.8 km² (Jana et al. 2012) with total population of approximately 5000. Several villages on the island, including Khasimara Char, Lakshmi Narayanpur, Khasimara, and Baishnabpara, have already been submerged (Jana et al. 2012; Ghosh et al. 2003). The shoreline changes observed in Ghoramara Island are largely the result of the estuarine hydrodynamics influenced both by natural processes and anthropogenic activities (Ghosh and Sengupta 1997).

Finally, Mousani Island covers 24 km^2, and, according to 2011 census figures, is home to about 22,000 people. This island is encircled by the Muriganga/ Bartala River to the west and northwest, Pitt's Creek/ Chenayer River to the east, and the Bay of Bengal to the south (WWF 2010). Mousani Island is a single Gram Panchayat (GP) unit, with four mouzas, under Namkhana CD Block.

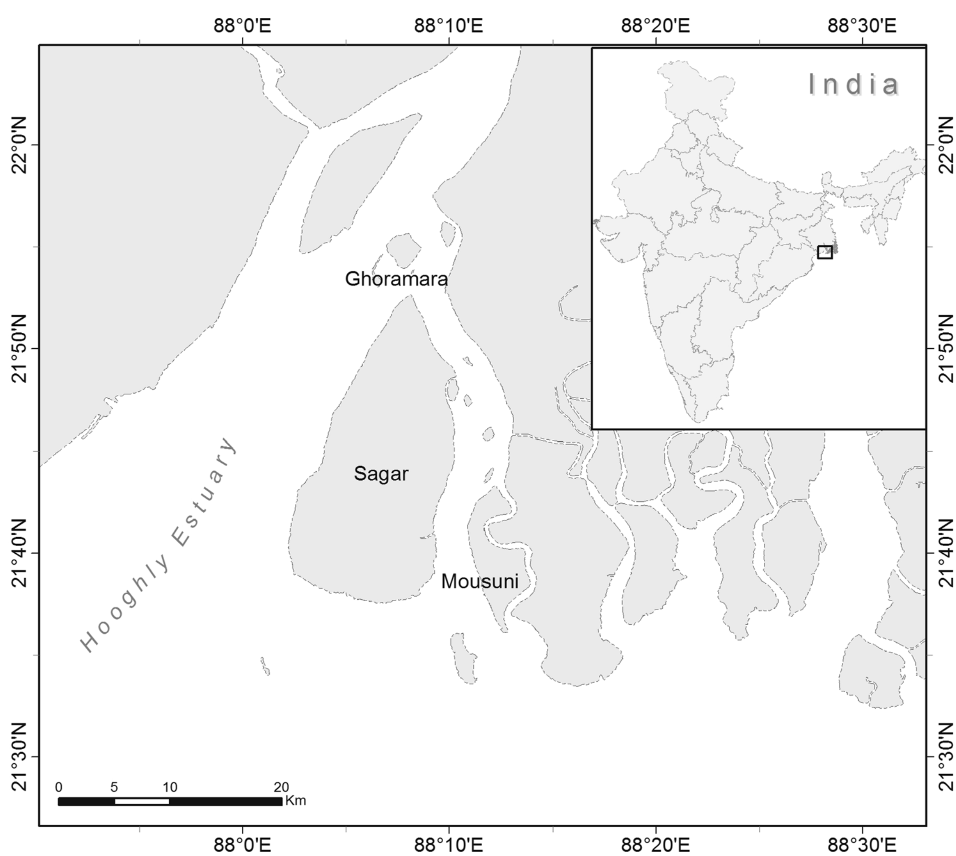

Fig. 2 Study area. (Source: School of Oceanographic Studies, Jadavpur University)

Data and methods

Data sources

This paper uses data from household surveys conducted for the purpose of this study through direct interviews with households within the study area of the Indian Sundarban Delta. To assess actual socio-economic conditions of the area, a thorough household-level socio-economic survey was conducted in the sampled villages of the study area during 2012 to 2013. A two-stage cluster random sampling was used for this study. In the first stage, mouzas were chosen randomly from all three islands; in the second stage, households within these areas were selected randomly for the survey. The survey was carried out through direct interviews in 52% of the inhabited mouzas of Sagar Block, including Ghoramara (22 mouzas out of 42) and 100% of the inhabited mouzas (four mouzas) of Mousani Gram Panchayat of Namkhana Block. One-to-one direct interviews were conducted between May 2012 and October 2013 with members of 783 households from 27 villages of the study area, consisting of a total number of surveyed populations of 4500. Almost 59% of mouzas were included to provide the required precision of the survey, but the number of households per mouza remained limited. The final questionnaire consisted of questions about household and individual level characteristics, such as age, sex, educational qualification, occupation, land use information, and other livelihood details. Other questions were asked concerning the impact of hazards and protection measures, including the major hazard type, type of losses from hazards, and use of flood shelter during extreme condition.

Key variables

The outcome variable used for the analysis is the binary variable measuring whether or not a household suffered a loss as a result of a natural hazard event. In our sample, 23% of all households reported a loss (Table 1). A loss may involve material goods, such as home, land, crops, livestock, or loss of life. 3.3% of all interviewed households reported more than one type of loss. Economic poverty has been estimated by the loss of agricultural land, property, and livelihood. A livelihood includes the capabilities, assets (including both material and social resources), and activities required for a means of living (Chambers and Conway 1992). A sustainable livelihood hence could adapt and recover from stress and shocks while maintaining or enhancing its capabilities in the future (Chambers and Conway 1992). Key explanatory variables in the analysis

Table 1 Summary statistics, Indian Sundarban household survey, 2012–2013

Sample characteristics	Mean/proportion	Comments
Effect of natural hazards		
% of HHs that experienced loss due to natural hazard (any) loss	23	
% of HHs that experienced loss of agricultural land due to natural hazard	11	
% of HHs that experienced other loss due to natural hazard	11	
Socio-economic characteristics		
% of HHs that are poor (based on normalised income)	24	
% of HHs that (based on official poverty line)	37	
% of HHs that experienced a surge	51	
% of HHs that experienced inundation	65	
% of HHs that who experienced erosion	28	
% of HHs that experienced salinization	9	
HH size	5.0	SD = 1.6; min = 1.0
Age of HH head	44.3	SD = 10.9; min = 19.0
% of HHs, where HH head is male	98	
% of HHs, where HH head is literate	84	
HH dependency ratio	39.1	SD = 44.8; min = 0
% of HHs that where at least one member of HH emigrated	27	
% of HHs reliant on ecosystem services	37	
Geographical location		
% of HHs living in Sagar Island	79	
% of HHs living in Ghoramara Island	6	
% of HHs living in Mousani Island	15	
Sample size = 783		

include normalised household income, type of natural hazard endured, reliance on ecosystem services, age and sex of household head, and household-level dependency ratio. Household income and the age of household head are measured on a continuous scale, while the remaining variables are either categorical or binary. Poverty status was defined in two different ways. First, a household was classified as poor if its income fell in the lowest quantile based on the quantile distribution of normalised income. Second, a household was considered to be poor if it was categorised as such by the Indian government. For a family of five, the all-India poverty line in terms of consumption expenditure would amount to about US $61.27 per month in rural areas and US $75.09 per month in urban areas (GOI 2013). Based on this definition, 37% of households fall below the poverty line. As highlighted previously, the main natural hazards experienced by the households include inundation and surges, land erosion, and soil salinization. Surge is the most frequent natural hazard, and 51% of households experienced this type of event. Soil salinization affected 9% of the interviewed households, while erosion was reported by 28% of all households in the study area.

Other controlling variables considered in the model include the standard socio-economic characteristics, i.e., household size, age, sex, and education of the household head and household-level dependency ratio [ratio between the number of dependents (aged 0–14 and over the age of 65) to the working population (aged 15–64)]. As can be seen from the summary statistics (Table 1), only 2% of household heads were female, indicating a strong gender bias in the study area. In addition, we controlled for household reliance on natural resources, which constitute an important source of income in Sagar, Ghoramara, and Mousani Islands. In this region, agriculture, fishing, aquaculture, and forestry are the predominant sources of income (World Bank Report 2014a; Hazra et al. 2014). Based on the responses provided by survey participants, households were considered to be reliant on the ecosystem if their source of income was predominantly at least one type of provisioning ecosystem services (cultivation, fishing, or aquaculture).

Methods

In terms of statistical modelling, we adapt a two-stage approach. First, we assess the impact of household poverty on the probability of material or life loss following a disaster. This analysis is conducted by means of logistic modelling. The logistic regression model equation is given by

$$\log it(Y_i = 1) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \dots + \epsilon_i; \quad i = 1 \dots n \tag{1}$$

where Y_i denotes the likelihood of material or life loss with values 0 or 1 (0 = no loss, 1 = loss), β_0 is a constant, X_j indicates household poverty status, and β_1 is the coefficient that shows the magnitude and direction of relationship with Y_i. X_{2i}, X_{3i}, X_{4i},… denote the controlling variables, such as type of natural hazard, household location, age, and education of the head of the household and reliance on ecosystem services. Finally, $\beta_{2,,}$ β_3, $\beta_{4\dots}$ denote adjacent coefficients to the corresponding variables and ϵ_i means error term.

Since land loss is the most frequently reported loss (14.8% of all households stated loss of land), in the second stage of the modelling, we assessed separately the effect of household poverty on loss of land vs. any other losses. While ideally, loss of life should be treated separately, the sample size of the households who reported such a loss is too small to examine this category separately. This analysis is undertaken using multinomial models, which are typically used when outcome variables are categorical and unordered. In multinomial logistic regression, associations are estimated using two separate regression equations. We use the following equations to estimate the results of multinomial logistic models:

$$\log\left(\frac{pi(Yi = j|X)}{pi(Yi = 0|X)}\right) = \beta_{10} + \beta_{11}X_{1i} + \beta_{12}X_{2i} + \beta_{13}X_{3i} + \dots + \beta_{1p}X_{pi}; \; i = 1 \dots n; j = 0, 1, 2 \tag{2}$$

where Yi is a categorical variable, and it can be 0, 1, and 2 which represents the likelihood of no loss, land loss, and other losses of the household, respectively. No loss (0) is considered as the reference category in this analysis. As in the first equation, X_{1i}–X_{pi} denote explanatory variables, while β_{11}–$\beta_{1p\dots}$ show the value and direction of the corresponding regression coefficients.

Model selection is done using the standard statistical tests, such as log likelihood ratio tests, the Akaike information criterion (AIC), and the Bayesian information criterion (BIC). Results are reported and discussed in the next section.

Results of multivariate analysis

As highlighted previously, the conceptual framework of this study draws from DPSIR framework highlighting the association between household poverty (state) and the likelihood of material and human loss (impact) influenced by natural hazards (driver pressure). The results presented here describe the relationships between poverty, environmental change, and vulnerability to natural hazards in the ISD. Situating these findings within the

DPSIR framework will improve our understanding of the overall risks facing these communities.

Tables 2 and 3 report the results of the regression analyses. Table 2 contains five separate models used to test our hypotheses as specified in the introduction. To examine the relationship between households' socio-economic vulnerability and the likelihood of loss following a hazardous event, we first tested the unadjusted effects of household wealth measured by wealth quantile (Model 1). The results of the unadjusted model show that for the richest households, the likelihood of suffering a loss following a natural hazard is significantly lower than for the poorest households ($p < 0.01$). When accounting for specific types of natural hazards endured by households, the effect slightly diminishes, although it remains highly significant (Model 2). Households which experienced erosion are significantly more likely to suffer from a loss than other households. The effects of a tidal surge and salinization are also strong, while the impact of inundation (not reported) is not statistically significant. This can be explained by the fact that the duration of inundation in these three islands is relatively short (less than half a day), and thus, the impact of

Table 2 Results of logistic regression to predict loss due to natural hazards in the Indian Sundarban Deltas

Loss due to natural hazard	Model 1 OR (CI)	Model 2 OR (CI)	Model 3 OR (CI)	Model 4 OR (CI)	Model 5 OR (CI)
Poverty					
HH wealth quintile					
Poor	0.64 (0.41; 1.00)**	0.64 (0.40; 1.03)*	0.71 (0.43; 1.17)		
Medium	0.44 (0.24; 0.79)***	0.51 (0.28; 0.95)**	0.54 (0.29; 1.03)*		
Rich	0.53 (0.31; 0.89)**	0.56 (0.32; 0.96)**	0.54 (0.30; 0.98)**		
Richest	0.43 (0.25; 0.74)***	0.48 (0.27; 0.85)**	0.52 (0.28; 0.95)**		
Reference: poorest	1.00	1.00	1.00		
HH is poor (based on official poverty line)				1.57 (1.11; 2.21)***	1.45 (0.99; 2.11)*
Natural hazards					
Tidal surge		2.08 (1.45; 3.00)***	1.99 (1.36; 2.92)***		1.94 (1.33; 2.84)***
Erosion		2.60 (1.78; 3.79)***	1.94 (1.28; 2.94)***		2.11 (1.40; 3.17)***
Salinization		2.38 (1.37; 4.13)***	2.48 (1.41; 4.36)***		2.36 (1.35; 4.13)***
HH socio-economic characteristics					
HH size			1.05 (0.93; 1.19)		1.09 (0.97; 1.23)
Age of HH head			1.02 (1.00; 1.04)*		1.01 (1.00; 1.03)
HH head is male			0.41 (0.12; 1.40)		0.36 (0.11; 1.23)
HH is literate			1.03 (0.62; 1.70)		1.04 (0.63; 1.72)
HH dependency ratio					
Medium			0.80 (0.51; 1.23)		0.79 (0.51; 1.22)
Low			0.52 (0.32; 0.84)***		0.55 (0.34; 0.89)**
Reference: high			1.00		1.00
At least one member of HH emigrated			1.46 (0.97; 2.20)*		1.41 (0.94; 2.12)*
HH is reliant on ecosystem services			0.83 (0.55; 1.24)		0.85 (0.56; 1.27)
HH location					
Mousani Island			6.04 (2.81; 12.98)***		6.75 (3.15; 14.44)***
Ghoramara Island			0.53 (0.29; 0.96)**		0.55 (0.30; 1.00)**
Reference: Sagar Island			1.00		1.00
Constant	0.47 (0.35; 0.64)***		0.22 (0.04; 1.07)*		0.13 (0.03; 0.63)**
Log likelihood	−405.27	−382.05	−358.69	−408.90	−360.34
LR chi2	13.81	60.24	106.97	6.54	103.67
p value	0.01	0.00	0.00	0.01	0.00
AIC	820.54	780.11	753.38	821.81	750.68
Number of observations	768	768	768	768	768

Significance levels *, **, ***are 90, 95, and 99%, respectively

Table 3 Results of multinomial regression to predict loss due to natural hazards in the Indian Sundarban delta household

Loss due to natural hazard (baseline: no loss)	Land loss RRR (CI)	Other loss RRR (CI)
Poverty		
HH is poor (based on normalised income)	1.22 (0.67; 2.21)	2.15 (1.27; 3.63)***
Natural hazards		
Surge	2.78 (1.62; 4.76)***	1.55 (0.96; 2.51)*
Erosion	1.96 (1.10; 3.48)**	1.97 (1.18; 3.29)***
Salinization	3.93 (2.03; 7.64)***	1.30 (0.55; 3.09)
HH socio-economic characteristics		
HH size	1.04 (0.89; 1.22)	1.07 (0.92; 1.25)
Age of HH head	1.01 (0.98; 1.03)	1.02 (1.00; 1.05)**
HH head is male	1.09 (0.12; 9.84)	0.24 (0.07; 0.92)**
HH is literate	0.74 (0.39; 1.38)	1.37 (0.70; 2.69)
HH dependency ratio		
Medium	0.55 (0.28; 1.07)*	0.53 (0.29; 0.96)**
High	0.97 (0.54; 1.74)	0.68 (0.39; 1.20)
Reference: low	1.00	1.00
At least one member of HH emigrated	1.16 (0.67; 2.02)	1.83 (1.10; 3.03)**
HH is reliant on ecosystem services	0.75 (0.43; 1.31)	0.84 (0.56; 1.26)
HH location		
Mousani Island	11.17 (4.74; 26.29)***	2.42 (0.86; 6.82)*
Ghoramara Island	0.41 (0.16; 1.08)*	0.62 (0.30; 1.27)
Reference: Sagar Island	1.00	1.00
Constant	0.04 (0.00; 0.49)**	0.07 (0.01; 0.43)***
Log likelihood	−464.52	
LR chi2	137.91	
p value	0.00	
AIC	989.04	
Number of observations	768	

Significance levels *, **, ***are 90, 95, and 99%, respectively

this natural hazard, compared to the consequences of other natural hazards, is less severe.

Model 3 controls additionally for household-level characteristics and geographical location of the household. It can be observed that wealth effects remain strong and significant only for the top two wealth quantiles. Controlling for other variables included in the model, the odds of a loss following a natural hazard for the richest households are 0.52 times the odds of the poorest households. It is also noteworthy that the age of the household head, household dependency ratio, and geographical location are all significant predictors of material and human loss. Households with an older head of household are significantly more likely to suffer from a loss following a natural hazard ($p < 0.10$). The result of Model 3 also illustrates the impact of migration. Households with at least one internal migrant (native to the area but not necessarily the present village) or out migrant (other places of the country) are more likely to suffer a human or economic loss. While the literature suggests that migration can have a positive effect on livelihoods through remittances (de Haas 2007; Erdal 2012; Viet 2008), it also alters household structure and household labour supply, which might have a negative impact on household ability to cope with the consequences of natural hazards. Because young people are most likely to leave, the remaining family members (mostly women, the elderly, and children) might experience higher vulnerability to extreme natural events. While migration can be considered a coping mechanism that reduces the long-term vulnerability (Black et al. 2013; McLeman and Smit 2006), we find that migration is associated with greater risk of loss following a natural hazard.

Models 4 and 5 provide an additional evidence by incorporating an alternative measure of poverty based on the proportion of population below the poverty line, as defined by the Government of India based on consumption expenditure for a family of five (SDG 2013). As can be observed in the unadjusted Model 4, the effect of poverty is strong, with the poorest households being at a significant disadvantage when it comes to the consequences of natural hazards

(OR 1.57, $p < 0.01$). Finally, Model 5 uses the same poverty measure but additionally controls for the type of natural hazards and household-level characteristics. Overall, the results are consistent with the findings reported in Model 3. Household wealth, geographical location, and type of natural hazards remain the strongest predictors of household loss following a hazardous event. Models 3 and 5, which control for a number of confounders, perform best based on their log likelihood values and AIC values. We also tested for interaction effects between poverty and type of natural hazards; however, no significant effects were found.

In Table 3, we report the results of the multinomial regression analysis with the outcome variable expressed as: land loss, other loss, and no loss (reference category). With regard to land loss, household poverty is no longer statistically significant, albeit marginally significant when no controlling factors are taken into account. The type of natural hazards and geographical location is the most important predictors for this category. Thus, *ceteris paribus*, for households that suffered from river salinization, the relative risk of land loss versus no loss would be expected to increase by a factor of 3.93. Tidal surge and erosion are also positively associated with land loss, while inundation has not been found to be a significant predictor of land loss, even in unadjusted models. Consistent with the results of the previous models (Table 2), households in Mousani Island are significantly more likely to suffer from land loss than households in Sagar Island, and the opposite is true for households located in Ghoramara Island. Finally, concerning the category of "other loss", which comprises both loss of life and material loss (other than land), additional significant effects can be noticed. In particular, the gender and age of the household head are associated with non-land loss following natural hazards. As only 2% of household heads are female, the association of gender with natural hazards may not be considered as significant. Results show female-headed households and households with older heads have a higher probability of enduring loss than male-headed households and households headed by younger individuals. This finding is consistent with previous literature (Ghosh 2012) showing that women in the Indian Sundarban are more vulnerable to negative consequences of natural hazards, as they have to work harder for livelihoods as limited options with low wage and have limited control over income and assets.

Discussion and policy implications

The deltaic islands of the Indian Sundarban Delta are highly vulnerable to the impacts of climate change and natural hazards. In addition, large proportions of the households in the study area are poor and thus have limited access to resources and facilities (Ghosh 2012). In this context, the main objective of this paper was to examine the significance and strength of the associations between household poverty, as a key aspect of vulnerability, and the effect of natural hazards on livelihoods, measured by material and human loss. The results of the study confirmed that the poorest households are most likely to suffer from deteriorating livelihoods following a natural hazard. Experiencing salinization was shown to have the greatest impact on the probability of land loss, while erosion and tidal surge are significant predictors of other types of loss (material or human). The impact of inundation (not reported) is not statistically significant. This can be explained by the fact that the duration of inundation in these three islands is relatively short (less than half a day), and thus, the impact of this natural hazard, compared to the consequences of other natural hazards, is less severe. Moreover, socio-economic factors, including household dependency ratio, the age of the household head, and geographical location, are all significant predictors of material and human loss. Controlling for other variables included in the model, households with a low dependency ratio are significantly less likely to suffer from material or human loss compared to households with a high dependency ratio. Controlling for socio-economic characteristics, the odds of suffering from land loss for households located in Mousani Island are 11 times higher than such odds for households located in Sagar Island. This can be explained by the differential developmental level of these two islands, in particular the considerably better infrastructure in Sagar Island. The study of Tessler et al. (2015), conducted on 48 major coastal deltas, suggests that countries with low GDP deltas are unable to make risk-reduction infrastructure investments face higher risks.

The results of the present study are largely in line with the existing body of evidence. Research by Rossi et al. (1983) on loss from natural hazards in the US between 1970 and 1980 showed that lower income households experience higher rates of injuries during natural hazards than more affluent households. According to the study of Fothergill and Peek (2004), the poor are more likely to die, suffer from injuries, and have proportionately higher material losses. Similar results were found in Ethiopia and Honduras, where the poorest households struggle most with hazardous shocks as preparedness measures are costly to adopt (Carter et al. 2007). Regarding the association between age of household head and loss, our findings are in line with Cherniack (2007), who indicated that older populations are significantly more likely to suffer from losses. Similar to other studies (Hazra et al. 2014; Myers et al. 2008), our results show that migration is positively associated with the probability of loss following a natural hazard. This might be explained by the fact that the rate of migration increases substantially after high-intensity climatic events, and as young people are most likely to leave, the remaining family members might experience higher vulnerability to extreme natural events. Our findings also show that amongst the three islands, households residing in Mousani Island were at greatest risk of being affected by both land and non-land losses. This can be explained by the fact that Sagar Island has a better infrastructural setup than Mousani Island, with good road connectivity, warning system, and embankment maintenance, which makes it more resilient to natural hazards than Mousani Island (HDR 2009; Andersen 2010; Dasgupta et al. 2006; Danda 2007).

Attaining sustainable development in low-elevation deltas is a major need due to their relatively lower adaptive capacity coupled with climate change and increasing sea level. Based on the conceptual framework of this study, we found positive association between economic poverty and material loss following natural hazard. In this context, strengthening links between poverty alleviation initiatives and disaster risk management should be the main focus for policy strategies. Here, we give several policy recommendations for improving system sustainability, accounting for the complex socio-ecological system of the Sundarban.

First, reduction of poverty may help lower the impact of loss on the economic condition of a household due to natural hazards. Development strategies, including efforts to improve income opportunities among the poor, are necessary to combat material losses from natural hazards. Frequent hazards adversely affect the livelihoods of poor people by continually damaging their means of earning income. Findings show that geographical location is a significant predictor of material losses. Planned rehabilitation could be a useful measure to reduce risk and resultant poverty mainly for Mousani Island which is at the greatest risk from losses. Mainstream disaster management generally does not focus on rehabilitation of peoples' means of livelihood; therefore, the affected households usually become more vulnerable to future risk due to repeated losses of livelihood. If households were able to save money from higher earnings, they could be better prepared for hazardous events when they occur. Creating livelihood options could be an efficient adaptation policy for poverty reduction, as diversifying sources of livelihoods is very important for increasing people's capacity to cope with adverse events and recover from any potential losses. For example, tourism could constitute an alternate livelihood option for the ISD, offering sandy beaches, scenic beauty, mangrove forests, and rich terrestrial and marine biodiversity. Environmentally sustainable tourism in Sundarban could be an important tool to improve the socio-economic status of the people of the ISD, provided that local communities are involved in government-led initiatives.

Second, development of community infrastructure can increase societal resilience, and reduce the intensity of natural hazard impacts. Sagar Island has better infrastructure with warning systems and flood shelters to better mitigate hazard impacts than the other two islands. According to the West Bengal State Action Plan 2012, building community resilience to withstand and recover from adversity following an extreme event could be achieved through such initiatives as capacity building and mobilizing communities. Infrastructure improvements, such as road construction, development of wireless networks, can improve modes of escape and communication during hazard events. It is evident from the field survey that embankments, maintained only by mud pilling, can become unstable and collapse during equinox tide in September. Construction of stable embankments along the sea and tidally influenced river, as well as regular repair and maintenance of embankments are particularly important, as tidal water topping and inundation is a driving issue in these islands. Improving the weather forecasting systems, and making them available to the entire population through the dissemination of key information should become a part of this integrated policy. Flood shelters should be established within reach of the communities. Participation of local people in disaster management training and mobilizing local communities to form disaster management teams could be a better planning strategy than stand-alone programmes administrated by the authorities. Community-based natural hazard management plans are necessary, as communities ultimately bear the consequences of natural hazards and are thus the main driving force in adapting to and mitigating the impacts of climate change. Given the interconnectedness of social and environmental issues and their global relevance, the lessons from the ISD could be adopted in other delta regions and beyond.

Acknowledgements This work was supported by the ESPA Deltas project (Grant No. NE/J002755/1) and the Belmont Forum DELTAS project co-funded by the Natural Environment Research Council (NERC) and the National Science Foundation (NSF) (Grant No. NE/L008726/1 and EAR-1342944). The Ecosystem Services for Poverty Alleviation (ESPA) programme is funded by the Department for International Development (DFID), the Economic and Social Research Council (ESRC), and the Natural Environment Research Council (NERC). This work is also a tribute to the "Sustainable Deltas 2015" (SD2015) Initiative endorsed by the International Council of Scientific Unions (ICSU), which aims to increase awareness of delta vulnerability worldwide and foster international collaboration, knowledge, and data exchange for actionable research toward delta sustainability. We gratefully acknowledge comments by Hao Xu, Omar de la Riva, Barbara Heitkamp, and Sayem Ahmed and comments by the handling Editor and anonymous reviewers.

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