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Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards

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Highlights

- Multi-hazard exposure, vulnerability and risk of deltaic social-ecological systems
- Novel modular, indicator library-based concept and methodology
- Consideration of hazard-dependent and independent vulnerability indicators
- Blueprint for vulnerability and risk assessments within and across deltas globally
- Ecological dimension should be considered more systematically in riskassessments

Abstract

Coastal river deltas are hotspots of global change impacts. Sustainable delta futures are increasingly threatened due to rising hazard exposure combined with high vulnerabilities of deltaic social-ecological systems. While the need for integrated multi-hazard approaches has been clearly articulated, studies on vulnerability and risk in deltas either focus on local case studies or single hazards and do not apply a social-ecological systems perspective. As a result, vulnerabilities and risks in areas with strong social and ecological coupling, such as coastal deltas, are not fully understood and the identification of risk reduction and adaptation strategies are often based on incomplete assumptions. To overcome these limitations, we propose an innovative modular indicator library-based approach for the assessment of multi-hazard risk of social-ecological systems across and within coastal deltas globally, and apply it to the Amazon, Ganges-Brahmaputra-Meghna (GBM), and Mekong deltas. Results show that multi-hazard risk is highest in the GBM delta and lowest in the Amazon delta. The analysis reveals major differences between social and environmental vulnerability across the three deltas, notably in the Mekong and the GBM deltas where environmental vulnerability is significantly higher than social vulnerability. Hotspots and drivers of risk vary spatially, thus calling for spatially targeted risk reduction and adaptation strategies within the deltas. Ecosystems have been identified as both an important element at risk as well as an entry point for risk reduction and adaptation strategies.

Keywords: spatial assessment, multi-hazard, index, Amazon delta, Ganges-Brahmaputra-Meghna delta, Mekong delta

1. Introduction

Coastal river deltas are low-lying areas built from sediments transported from upstream and constantly reshaped by the forces of river and tidal water. Within coastal deltas, the patchy transitions between land, fresh, brackish and saline water generate diverse habitats and exceptional biodiversity offering a multitude of ecosystem services (Campell, 2012). Intensive agricultural production is typically possible thanks to nutrient-rich sediment deposition. Abundant waterways connect settlements and offer opportunities for navigation and transport within the delta and to inland locations. Serving as life support systems, deltas have attracted human settlement for thousands of years and even nurtured the formation of human civilization (Bianchi and Allison, 2009; Pennington et al., 2016). Today almost 360 million people live in river deltas (Higgins, 2016)with an average population density of approximately 600 people/km2 – an order of magnitude greater than the average population density of the globe (Ericson et al., 2006; Higgins, 2016).

Despite considerable advantages, deltaic environments also challenge human activities as these dynamic landscapes (shifting distributaries, erosion and aggradation processes, etc.) tend to have high levels of exposure to multiple (socio-) natural hazards, such as river and tidal flooding, droughts, river bank and coastal erosion, cyclones, storm surges, tsunamis and sea water intrusion (Sebesvari et al., 2016a, 2016b). Some deltas also face additional threats such as earthquakes (Steckler et al., 2008).With rapid urbanization, societal transformation and environmental (including climate) change, it is likely that hazards, vulnerabilities, and associated disaster risk will further intensify in many deltas around the world (Hinkel et al., 2014; IPCC, 2012; Syvitski et al., 2009), undermining sustainable development in these coastal zones of high ecological, economic, and hence societal relevance.

Human interventions to (i) tame the dynamic character of the landscape, (ii) exploit natural resources and (iii) reduce exposure to prevailing hazards has led to massive infrastructure development such as canal systems for irrigation and transport, the conversion of wetlands and forests to agricultural, urban and industrial areas (Kuenzer et al., 2014), and the establishment of protective infrastructure to mitigate hazards such as flooding in many deltas around the world. A 52% decline of wetland coverage was recorded between the 1980s and early 2000s in major river deltas (Coleman et al., 2008). Building of upstream dams and reservoirs significantly reduces the amount of sediment reaching the deltas and thus, combined with unsustainable groundwater extraction, contributes to the subsidence of deltas globally (Syvitski et al., 2009). Together with rising sea levels (Horton et al., 2014), significant inundation of land resources and salinization of freshwater resources far inland is projected in many deltas (Giosan et al., 2014). Thus, deltaic landscapes will likely struggle to maintain their structural and functional features (Day et al., 2016; Renaud et al., 2013).

Being hotspots of ongoing and projected global change impacts, as well as highly populated, ecologically and economically important sentinels of sustainable development, the state and fate of deltaic social-ecological systems (SES) has great significance locally, nationally and globally. Delta futures will therefore either greatly enhance or detract progress towards achieving the Sustainable Development Goals (SDGs), notably SDG1 (No Poverty), SDG2 (Zero Hunger), SDG6 (CleanWater and Sanitation), SDG11 (Sustainable Cities and Communities), SDG 13 (Climate Action), SDG 14 (Life BelowWater), and SDG 15 (Life on Land) as well as the targets of the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sebesvari et al., 2016a). Assessment of the risks faced by and within deltas based on cross-sectoral and cross-boundary indicators and targets will be key for the identification of targeted risk reduction, resilience-building and adaptation strategies (Chapman and Darby, 2016), and hence the sustainable development of these hotspots for climate change impacts (Szabo et al., 2016a).

To date, vulnerability and risk in deltas is mostly characterized with respect to single hazards (Birkmann et al., 2012; Dinh et al., 2012; Mansur et al., 2016), either at the delta scale (Tessler et al., 2015) or based on case studies at the local level (de Andrade et al., 2010; Dinh et al., 2012; Few and Tran, 2010; Islam et al., 2013). Intermediate, sub-delta scale assessments which enable cross-delta comparisons while also delivering planning-relevant information on the scale of sub-delta administrative units are absent (Sebesvari et al., 2016b; Wolters et al., 2016). While the need for considering and analyzing deltas as coupled SES has been increasingly highlighted over the past several years (Brondizio et al., 2016; Day et al., 2016; Szabo et al., 2016b), the majority of existing vulnerability and risk assessments still focus largely on the social and/or economic dimension (Balica et al., 2012; Birkmann et al., 2012; Burton and Cutter, 2008; Chen et al., 2013; Few and Tran, 2010; Mansur et al., 2016; Mondal, 2013; Tessler et al., 2015). Currently integrated assessments focusing on deltas as coupled SES are rare (Lázár et al., 2015; Wolters and Kuenzer, 2015; Sebesvari et al., 2016a, 2016b). As a result, vulnerability and risk in areas with strong social and ecological coupling, such as coastal deltas, is not fully understood and the identification of risk reduction and adaptation strategies are often based on incomplete assumptions.

Risk-informed planning of future development as well as targeted disaster risk reduction (DRR) and adaptation strategies and measures (including ecosystem-based options)will not only be important, but existential in deltas in the coming decades. This requires spatially explicit information on the exposure, vulnerabilities and risks associated with different combinations of hazards within deltas in an integrative manner, not only focusing on societal aspects or ecosystems alone, but on interconnected deltaic SES.

Addressing the gaps and challenges described above, we present an innovative assessment concept and indicator-based methodology that is sensitive to the specific (multi-) hazard setting in a given delta and can be used as a blueprint for SES-centered spatially explicit vulnerability and risk assessments across and within deltas globally: the Global Delta Risk Index (GDRI). The GDRI presented here uses a modular indicator library-based approach that has been co-developed and piloted with local and regional stakeholders in three globally relevant mega-deltas: the Mekong delta, the Ganges-Brahmaputra-Meghna (GBM) delta, and the Amazon delta.

2. Materials and methods

The GDRI was constructed building on and extending a multi-step, iterative workflow for index construction and risk assessment (OECD, 2008; Hagenlocher and Castro, 2015; Asare-Kyei et al., 2017). A spatial approach that uses sub-national administrative units was selected to enable cross-delta comparisons of risk while providing information at the sub-delta scale to enable spatially informed local decision-making and intervention planning. The conceptual framework, including major risk components and vulnerability domains, was first defined.

2.1. Framing vulnerability and risk

Over the past decades, conceptual approaches on how to understand risk resulting from human-environment interaction have undergone considerable paradigm shifts from environmentally deterministic, hazard-centric approaches (White, 1973) to political economy and political ecology perspectives (Blaikie et al., 1994; Hewitt, 1983; Lewis, 1999; O'Keefe et al., 1976; Wisner et al., 2004), and finally to holistic concepts that integrate and connect social, economic, political, environmental and governance-related drivers of disaster risk (Birkmann et al., 2013; Eakin and Luers, 2006; IPCC, 2014; Sebesvari et al., 2016b; Turner et al., 2003). Associated theoretical frameworks and models have been instrumental in two main ways: first, in conceptualizing and systematizing vulnerability and risk by sketching out key components and thematic dimensions, and second, by serving as an important first step towards the assessment of vulnerability and risk; for example by guiding the selection of relevant indicators and their combination in a meaningful index. Recognizing the need to consider deltas as coupled SES (Brondizio et al., 2016; Szabo et al., 2016b; Wolters and Kuenzer, 2015) and hence vulnerability of SES (Adger, 2006; Eakin and Luers, 2006; Turner et al., 2003), the GDRI builds on a simplified, inclusive SES-centered vulnerability and risk framework proposed by Sebesvari et al. (2016b) that was adapted from Turner et al. (2003) to fit the idiosyncrasies of deltaic environments. Following conceptualizations by Wisner et al. (2004) and others, in this framework risk is defined as the potential for adverse consequences resulting from the interaction of one or multiple (socio-) natural hazards with vulnerable elements of the SES exposed to these hazards (here operationalized as risk = hazard exposure × vulnerability). Hazards are operationally defined as the potential occurrence of sudden onset or slow onset natural, anthropogenic or coupled physical events or processes that may cause loss of life, injury, or other health impacts, as well as loss and damage to elements and processes of the SES in place (IPCC, 2014). Exposure refers to the extent to which elements and processes of the SES are in the reach or subjected to one or multiple hazards (IPCC, 2014). Vulnerability is understood as the predisposition of the elements and processes of the SES to be adversely affected (IPCC, 2014) and is composed of four intertwined components in the GDRI: social susceptibility, ecosystem susceptibility, lack of capacity to cope and adapt, and lack of ecosystem robustness (Sebesvari et al., 2016b).

Fig. 1 shows the concept and modular structure of the GDRI that was used to assess exposure, vulnerability, and risk of SES to both single or multiple hazards in the three case study deltas, and which – along with an associated ‘library’ of hazard-dependent and independent indicators (Supplementary Material 1) – can be used as a blueprint for further assessments across and within deltaic environments globally. It presents the overall structure and aggregative flow of the GDRI from the indicator level (at the bottom of Fig. 1), to vulnerability domains (i.e. susceptibility of the SES, lack of capacities/ecosystem robustness), risk components (i.e. hazard exposure and vulnerability of the social-ecological system) and final aggregated risk. Following the logic of the modular indicator library, the number of vulnerability indicators varies depending on the hazard. The numbers describe how many indicators are listed for each hazard in the indicator library (Supplementary Material 1).

Fig. 1. The Global Delta Risk Index (GDRI): concept and structure. Risk is understood as a function of (i) hazard exposure and (ii) vulnerability of the SES. It is operationalized applying a modular, flexible indicator set consisting of both hazard-dependent and independent indicators while being responsive to the specific (multi-) hazard setting in a given delta.

2.2. Indicators and data collection

Relevant hazards and potentially exposed elements of the SES as well as associated hazard-dependent and independent vulnerability indicators (incl. potential proxy indicators) were identified through a combination of the outcomes of a systematic review of scientific literature on vulnerability indicators in deltaic SES (detailed in Sebesvari et al., 2016b) and participatory expert consultations during a series of stakeholder workshops in the three deltas between 2014 and 2016. The three workshops (one in each delta) were attended by representatives from local/regional sectoral agencies (i.e. planning, disaster risk management, health, agriculture, and forestry), academia, and civil society, and aimed at understanding the SES and identifying both relevant hazards and associated vulnerability indicators in each delta. These indicators were organized in a modular indicator library (Supplementary Material 1) which distinguishes between hazard-dependent and independent vulnerability indicators as well as potential proxies. Third, data for the three deltas were acquired from multiple sources (incl. census data, publicly accessible national and global repositories, as well as directly from scholars who have published on these deltas; see acknowledgements) for the different components of the risk framework: (i) hazard (flooding, cyclones, salinity intrusion, and storm surges), (ii) exposed elements of the SES (i.e. gridded population and land use/land cover data) and (iii) vulnerability of the SES. Since no reliable, comparable data on drought occurrence probability currently exist for the three deltas, probabilistic drought maps were developed for all deltas based on Standardized Precipitation Index (SPI-3) data by using an extreme value modeling approach adapted from Bordi et al. (2007).

2.3. Constructing the Global Delta Risk Index

In constructing the GDRI a spatially explicit approach was pursued. However, due to the paucity of spatially explicit data (i.e. gridded datasets) for many of the indicators, the final calculation of the index was conducted at the sub-national scale using administrative units. The deltas extent dataset published by Tessler et al. (2015) was used to delineate the study area in the three pilot deltas. Exposure of the SES to a single hazard was assessed by calculating the average percentage of both people and ecosystems in hazard-prone areas using gridded data and a spatially explicit approach in a Geographic Information System (GIS). Since people and ecosystems can be exposed to multiple hazards, relative exposure to individual hazards was summed to derive multi-hazard exposure of the SES. To enable cross-delta comparisons of multi-hazard exposure (HAZEXPSES), the final score was divided by five – the maximum number of hazards considered in the analysis. For the vulnerability assessment, following data acquisition, preprocessing of the data was performed using GIS. This includes the calculation of density surfaces (e.g. density of the transportation network, evacuation/shelter places, and emergency services), transformation of absolute into relative values, and calculation of zonal statistics (mean, max) to convert gridded datasets into one score for each administrative unit within the deltas. As a fourth step, an analysis of missing data was performed with no issue observed. Next, potential outliers in the data were examined using both box plots based on the inter-quartile range (i.e. data outside 1.5 × IQR) and skewness and kurtosis of the data (Supplementary Material 2). Triangulation was used to verify or falsify potential outliers, and, where relevant, extreme values were treated using a winsorization approach. As a sixth step, multicollinearities within each of the four vulnerability domains were assessed using

Kendall's Tau, a non-parametric correlation coefficient that can be used to assess and test correlations between variables in research contexts with small sample sizes, with r N 0.9 indicating highly collinear datasets. Statistical significance was tested using a two-tailed approach. Following this approach, no issue of multicollinearity was detected (Supplementary Material 2). Both analysis steps were conducted in SPSS (IBM SPSS Statistics). Linear min-max normalization was applied to rescale the indicators to a range between zero and one. To render the datasets comparable, the lowest min and highest max values across the three deltas were used in the normalization process for all three deltas. Indicators where high scores would contribute to reduced vulnerability and risk (see indicator library; Supplementary Material 1) were inverted during the normalization process. In step eight, the pre-processed and normalized indicators (x_i') were combined into the four vulnerability domains (*VD*; i.e. ecosystem susceptibility, social susceptibility, lack of ecosystem robustness, and lack of coping/adaptive capacities) using additive aggregation (Eq. (1)). Following the modular structure of the indicator library, only those indicators were considered that are relevant for the specific (multi-)hazard setting in the three deltas as defined by stakeholder input.

$$VD = \sum_{i=1}^{n} (w_i * x_i') \tag{1}$$

While the design of the GDRI (Fig. 1) principally enables users to specify weights (w_i) for each normalized indicator (x_i'), for example through expert consultation, equal weights were applied for the construction of the GDRI in the three case study deltas. To analyze vulnerability domains of the SES (VD_{SES}), social and ecosystem susceptibility were aggregated into a metric representing susceptibility of the SES while lack of coping/adaptive capacities was combined with lack of ecosystem robustness into a metric representing the lack of capacities/robustness of the SES and applying equal weights (Eq. (2)).

$$VD_{SES} = \sum_{j=1}^{n} (w_j * VD_j) \tag{2}$$

The two vulnerability domains of the SES, i.e. susceptibility of the SES (VD_{SES1}) and lack of capacities and robustness of the SES (VD_{SES2}), were then further combined into an index score representing vulnerability of the SES (VU_{SES}) using the average of the two (Eq. (3)).

$$VU_{SES} = \left(\frac{VD_{SES1} + VD_{SES2}}{2}\right) \tag{3}$$

Ultimately, following the modular framework, (multi-) hazard exposure and vulnerability of the SES were combined in a (multi-hazard) risk index ($RISK_{SES}$) through multiplicative aggregation, whereby both risk components are weighted equally. Thereby, the hazard component of the framework was indirectly considered in the exposure term of the equation following existing risk assessment approaches (Hagenlocher and Castro, 2015; BEH and UNU-EHS, 2016; Wannewitz et al., 2016). Aggregation of indicators and domains was carried out in Excel and results visualized in a GIS. Results are presented in Fig. 2.

$$RISK_{SES} = HAZEXP_{SES} \ x \ VU_{SES} \tag{4}$$

2.4. Reliability analysis

Drawing on a metric developed in the context of the Index for Risk Management (INFORM; http://www.inform-index.org), a reliability index was developed and applied to each of the three deltas to increase transparency regarding the quality of data used to calculate the GDRI. Adjusted from the INFORM reliability metric, it takes into account the following criteria: (i) percentage of imputed data across indicators, (ii) percentage of hazard data available, (iii) percentage of proxy indicators, (iv) percentage of indicators at provincial level (here assumed to be positive, although higher spatial resolution would be desirable), and (v) recency (average age) of the data. The corresponding scores for each criteria were rescaled to values between zero and one, aggregated, and averaged in order to derive the final reliability scores. In this context a score of 1 represents high reliability and a score of 0 implies low reliability. Since the GBM delta is located both in India and Bangladesh, the reliability index was computed for each country separately (Supplementary Material 2). All analyses were performed using Microsoft Excel.

2.5. Data availability

The data that support the findings of this study are provided as Supplementary Data 1. Supplementary Material 3 provides an overview of the datasets and sources for each of the indicators that were used to construct the GDRI.

3. Results

3.1. Multi-hazard risk of deltaic social-ecological systems

Using the GDRI framework and approach, we assess single and multi-hazard exposure, vulnerability, and risk of SES across and within the three deltas (Table 1). While deltas are generally confronted with a number of climate and non-climate related hazards, the assessment focuses only on those hazards that were mentioned as relevant by the local stakeholders during the workshops in the respective deltas, i.e. flooding, drought, and salinity (for all deltas) as well as cyclones and storm surges (only for the GBM delta) and where data were available. We show that average multi-hazard risk is highest in the GBM delta (0.21 in a range from 0 to 1) and lowest in the Amazon delta (0.09 in a range from 0 to 1) with the largest within-delta variability in the GBM delta. The latter effect is partially strengthened by the fact that the GBM is shared among two distinct neighboring countries – India and Bangladesh. On average, multi-hazard risk is higher in the Bangladeshi portion (risk score: 0.22) as compared to the Indian portion of the GBM delta (risk score: 0.14). Being prone to multiple hazards (i.e. flooding, droughts, salinity intrusion, cyclones and storm surges), SES exposure is highest in the GBM delta, followed by the Mekong delta which features high exposure to flooding in the upstream parts of the delta, high exposure to droughts in the southern parts of the delta and high exposure to salinity intrusion along the coastline. Multi-hazard exposure is lowest in the Amazon delta, where primarily the southeastern municipalities are affected by both flooding and droughts (Table 1).

Table 1
Multi-hazard risk, hazard exposure, and vulnerability of the SES across the three deltas.

	Multi-hazard risk of SES		Multi-hazard exposure of SES		Multi-hazard vulnerability of SES		Multi-hazard susceptibility of SES		Multi-hazard lack of capacities / robustness of SES	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Amazon	0.09	*0.04*	0.17	*0.08*	0.51	*0.02*	0.42	*0.04*	0.59	*0.03*
GBM	0.21	*0.12*	0.34	*0.19*	0.62	*0.04*	0.50	*0.04*	0.73	*0.05*
Mekong	0.16	*0.05*	0.31	*0.11*	0.51	*0.02*	0.42	*0.02*	0.61	*0.02*

Disaggregating the highly aggregated index, the analysis further reveals major differences between social and environmental vulnerability across the three deltas, notably in the Mekong and the GBM deltas where environmental vulnerability is significantly higher than social vulnerability. Environmental vulnerability is highest in the GBM and lowest in the Amazon delta while social vulnerability is highest in the GBM and lowest in the Mekong delta. In all deltas, social and ecological susceptibility scores are lower than those representing the lack of short-term coping and long-term adaptive capacities or the lack of ecosystem robustness (Table 2).

Table 2
Decomposing multi-hazard vulnerability of SES across the three deltas.

	Social vulnerability (multi-hazard)	Environmental vulnerability (multi-hazard)	Social susceptibility (multi-hazard)	Ecosystem susceptibility (multi-hazard)	Lack of coping & adaptive capacities (multi-hazard)	Lack of ecosystem robustness (multi-hazard)
	Mean	Mean	Mean	Mean	Mean	Mean
Amazon	0.52	0.49	0.47	0.37	0.57	0.61
GBM	0.56	0.67	0.40	0.60	0.71	0.74
Mekong	0.37	0.66	0.29	0.54	0.44	0.78

Key drivers of ecosystem susceptibility in all deltas include freshwater scarcity and low soil organic matter. Additionally low forest connectivity and low species richness are important drivers of ecosystem susceptibility in the GBM and Mekong deltas, whereas additional relevant drivers include the likelihood for groundwater pollution (probability of arsenic in groundwater) in the GBM, and low cation exchange capacity of the soil in the Amazon delta respectively. Low coverage by protected areas is an important factor influencing the lack of ecosystem robustness in each of the deltas. Additionally, decreased ecosystem functionality and species abundance are important drivers in the GBM and Mekong deltas.

Fig. 2 shows spatial multi-hazard risk patterns and variability for SES both across (Fig. 2, panel A) and within (Fig. 2, panel B) the three deltas at the sub-delta scale (i.e. for 49 municipalities in the Amazon delta, for 59 districts in the GBM delta and for 13 provinces in the Mekong delta). Yellow represents lower multi-hazard risk, while darker shades of red indicate higher levels of multi-hazard risk.

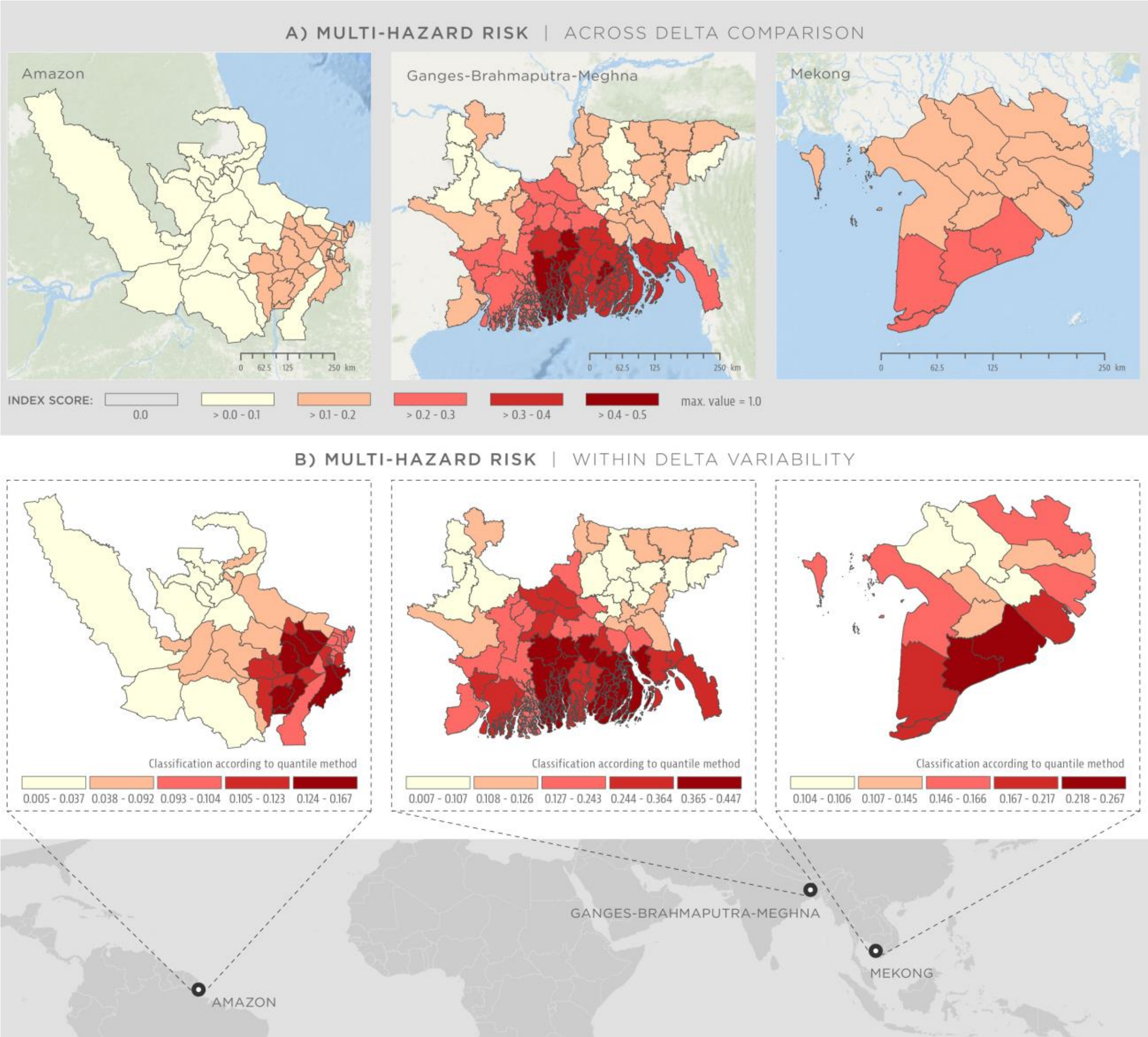

Fig. 2. Multi-hazard risk of the social-ecological system: (A) across and (B) within deltas. Note: Visualization in Panel B is based on quantiles, i.e. colors are not comparable across deltas.

The variability of the main components of multi-hazard disaster risk – hazard exposure and vulnerability of the SES – is visualized in Fig. 3 for each of the sub-delta administrative units, with the greatest variability in the GBM delta. This highlights that differences in multi-hazard risk across and within the three deltas are largely driven by variations in exposure given that overall vulnerability of the SES is similarly high (between 0.51 and 0.62) in all deltas. However, the risk profiles show that the drivers of vulnerability, despite similar overall vulnerability scores, vary between sub-delta regions.

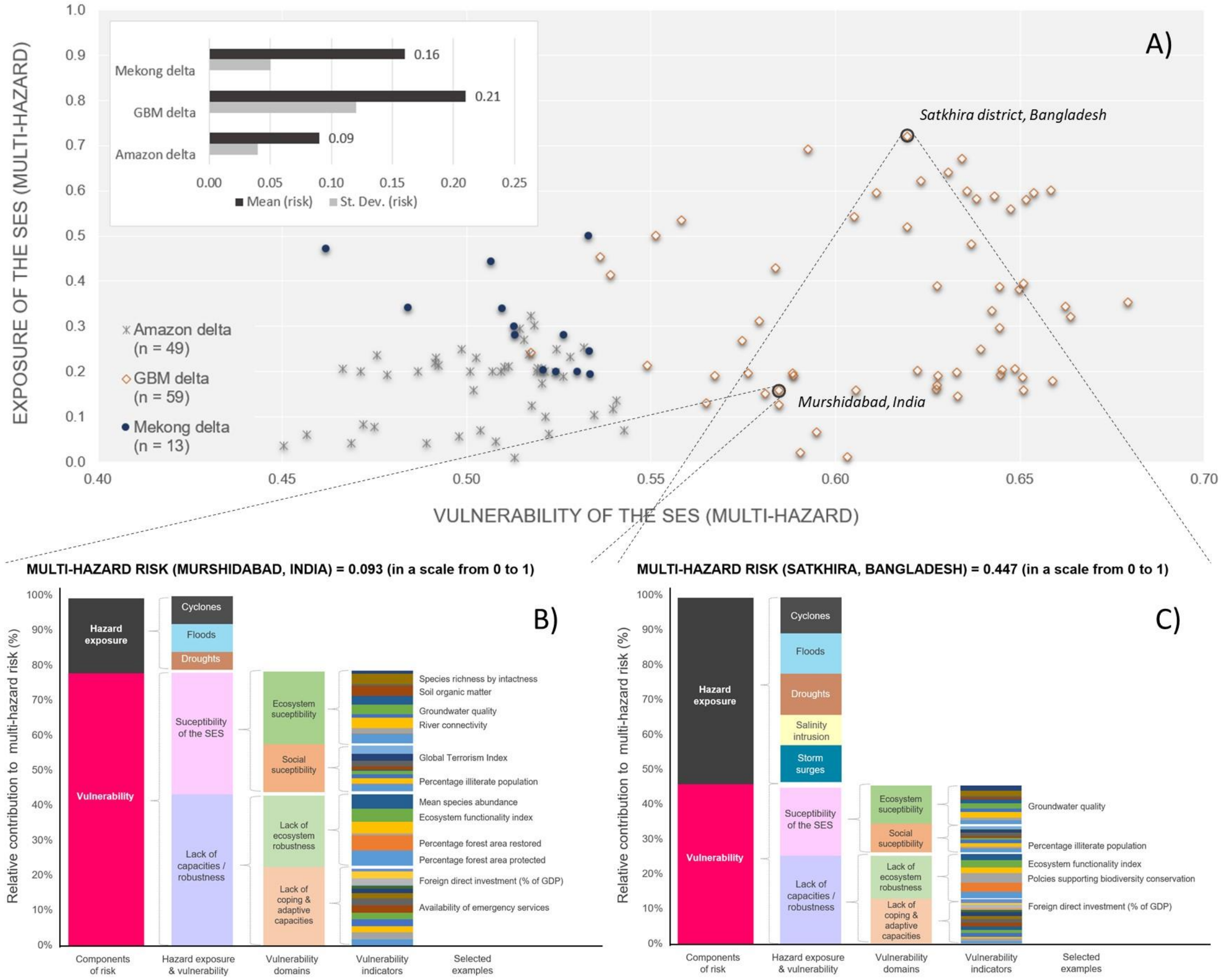

Fig. 3. Risk profiles in the Amazon, GBM, and Mekong delta: based on variability in multi-hazard exposure and vulnerability of SES across deltas (Panel A). Panels B and C show the relative contribution of the risk components, vulnerability domains and indicators to the final risk scores for two selected districts in the GBM delta, constituting illustrative risk profiles.

3.2. Reliability

On a scale from 0 (lowest reliability) to 1 (highest reliability), reliability scores of 0.74, 0.79 and 0.81 were calculated for the Amazon, the GBM and the Mekong Delta, respectively. The assessment shows that the risk estimates of all deltas were calculated based on relatively recent data with an average age of around 3 years but suffered from a lack of data available at the provincial level and relatively frequent use of proxy indicators (Supplementary Material 2).

3.3. Indicator library

Relevant indicators representing vulnerability of deltaic SES were added to an indicator "library" (Supplementary Material 1) that can support future assessments of vulnerability and risk in deltas. In the library indicators are organized according to the four main vulnerability domains (social susceptibility, ecosystem susceptibility, lack of coping and adaptive capacities, lack of ecosystem robustness) in a modular structure, i.e. according to their relevance for the six different (socio-)natural hazards relevant in the three deltas considered in this analysis: (i) cyclones, (ii) drought, (iii) floods (pluvial/fluvial), (iv) salinity intrusion, (v) storm surges, and (vi) pollution. The library can easily be extended if applied in different delta settings, for example by considering additional hazards. The library comprises indicators that can be represented in a spatially explicit manner (e.g. deforestation, wetland loss, forest connectivity, or travel time to the closest city), at the level of administrative units (e.g. illiteracy, dependency ratio, or poverty), as well as indicators on policy processes that affect an entire delta (e.g. existence of disaster risk management and/or adaptation strategies, integrated development plans, or policies contributing to biodiversity conservation or coastal protection). Distinguishing between hazard-dependent and independent indicators, the modular approach is responsive to the specific (multi-)hazard setting of a given delta, enabling developers of future (multi-hazard) vulnerability and risk assessments to include only those indicators that are relevant for a particular hazard configuration within the delta. Next to the modular set of indicators, a list of potential proxy indicators – that can be used when appropriate data to represent the actual vulnerability indicators do not exist (e.g. when conducting assessments in data scarce environments) – is proposed. These proxy indicators were identified during the review of scientific literature by Sebesvari et al.

(2016b), during the stakeholder workshops in the three deltas, and by analyzing correlations (in SPSS software) between indicators where data were available for the three deltas. Table 3 provides an overview of the number of indicators in each vulnerability domain in the indicator library as well as the final number of indicators that were included in the assessment considering data availability in the three deltas.

Table 3
Number of vulnerability indicators relevant for specific hazards (library vs. used in the assessment).

	Social susceptibility		Ecosystem susceptibility		Lack of coping capacity		Lack of adaptive capacity		Lack of ecosystem robustness	
	Library	*Used **	Library	*Used **	Library	*Used **	Library	*Used **	Library	*Used **
Flooding[a]	21	*13 (62%)*	11	*8 (73%)*	25	*16 (64%)*	11	*3 (27%)*	15	*8 (53%)*
Droughts[a]	18	*11 (61%)*	14	*10 (71%)*	23	*15 (65%)*	13	*3 (23%)*	17	*8 (47%)*
Storms[b]	20	*13 (65%)*	5	*3 (60%)*	24	*16 (67%)*	11	*3 (27%)*	16	*8 (50%)*
Storm surges[b]	21	*13 (62%)*	8	*4 (50%)*	24	*16 (67%)*	11	*3 (27%)*	16	*8 (50%)*
Salinity intrusion[c]	13	*9 (69%)*	9	*5 (56%)*	21	*13 (62%)*	13	*3 (23%)*	15	*7 (47%)*
Pollution[d]	14	*0 (0%)*	11	*0 (0%)*	19	*0 (0%)*	10	*0 (0%)*	17	*0 (0%)*
Total number	**23**	***13 (57%)***	**16**	***11 (69%)***	**26**	***16 (62%)***	**13**	***3 (23%)***	**17**	***8 (47%)***

* to enable comparability across the three deltas, indicators were only included in the assessment if data was available for all three deltas (the Amazon delta, the GBM delta, and the Mekong delta). During the data acquisition process it became evident that data availability also varies across deltas. [a] relevant in all three deltas; [b] relevant only in the GBM delta; [c] relevant in all three deltas, but data only available for the GBM and Mekong delta; [d] relevant in all three deltas, but no data available for all deltas.

4. Discussion and further research

Despite the progress that has been achieved in DRR at national and local levels over the past several decades, disasters resulting from the interaction of (socio-) natural hazards with increasing exposure and high levels of vulnerability of SES continue to undermine sustainable development and pose a challenge to achieving the SDGs. As a consequence, the Hyogo Framework for Action (2005–2015) and the more recently adopted Sendai Framework for Disaster Risk Reduction (2015–2030; UNISDR, 2015) call for a better understanding of disaster risk (priority 1 in the Sendai agreement) and enhanced efforts to reduce exposure and vulnerability and build resilience at all levels using inclusive, multi-hazard approaches. Next to identifying drivers of disaster risk, this also requires the assessment and monitoring of disaster risk. Despite the clearly articulated urgency for assessments in the global DRR agenda and the recognition of the need for assessing the vulnerability of SES (Turner et al., 2003; Eakin and Luers, 2006; Fuchs et al., 2012), notably in coastal deltas that are shaped by intensive human-environment interaction and exposure to multiple hazards (Brondizio et al., 2016; Sebesvari et al., 2016b), to our knowledge no approach exists to date that can be used for the spatial assessment and monitoring of vulnerability and risk of SES in a multi-hazard setting. The presented GDRI addresses these gaps, and constitutes a novel, transparent, indicator library-based concept and methodology for the integrated assessment of single or multi-hazard vulnerability and risk across and within deltaic SES. Our results confirm the need emphasized by De Lange et al. (2010) to systematically consider indicators of environmental vulnerability when assessing disaster risk and identifying risk reduction and adaptation strategies, while reemphasizing the need for enhanced efforts to sustainably manage, conserve, and restore ecosystems and their services. Through its modular design, the GDRI also overcomes the limitations of existing multi-hazard risk assessment approaches that do not differentiate between hazard-dependent and hazard-independent indicators (Greiving, 2006; Liu et al., 2013; BEH and UNU-EHS, 2016; Wannewitz et al., 2016) – a need that has been underscored in recent reviews of multi-hazard risk methodologies for natural hazards (Kappes et al., 2012; Gallina et al., 2016). Going beyond case studies at the local level (de Andrade et al., 2010; Birkmann et al., 2012; Dinh et al., 2012; Islam et al., 2013) and global assessments that do not capture differences in vulnerability and risk within deltas (Tessler et al., 2015), the sub-delta scale applied here enables the identification of hotspots and variability of risks within deltas. It is thus in line with the need to "develop, periodically update and disseminate, as appropriate, location-based disaster risk information, including risk maps, to decision makers, the general public and communities at risk" as articulated in the Sendai agreement (UNISDR, 2015, p.15).

As pointed out by de Sherbinin et al. (2017, p.415), "indicators and indices can help to reduce complexity in policy-relevant ways, providing an important link between science and policy and helping to point decision-makers towards potential solutions to problems at the human–environment interface." This has also been highlighted by Abson et al. (2012, p. 523) who conducted a study on vulnerability of SES in the Southern African (SADC) region and concluded that from a policy perspective "contextualized, 'information-rich' vulnerability indices can prove useful as they provide a compromise between the rich and difficult to interpret detailed information provided by a large suite of individual vulnerability indicators and easy to visualize, but potentially 'information poor', aggregate vulnerability indices." This is particularly relevant in the adaptation arena, where millions of dollars are already being spent or will be spent in the decade to come, and where spatial prioritization is key (de Sherbinin et al., 2017). The presented approach can inform delta development planning, such as those strategic plans published for the Mekong delta (Government of Vietnam and Dutch Government, 2013) and the GBM delta (http://www.bangladeshdeltaplan2100.org) by highlighting the fact that different regions of a delta are exposed to different hazards or combinations of hazards and have consequently different vulnerabilities and risks. Decomposing the GDRI into its risk components (hazard exposure and vulnerability), vulnerability domains (susceptibility of SES and lack of capacities/robustness of SES), and their underlying indicators (Fig. 3) for use by decision makers, practitioners, and analysts, supports the identification and definition of spatially targeted risk reduction and adaptation strategies and/or measures. Web-based approaches that enable an interactive visualization and querying of the results and associated risk profiles can be instrumental for such purposes (Kienberger et al., 2013) and will be compatible with the modular structure of the GDRI. The associated indicator library enables the further transferability of the presented concept and methodology to deltas globally. Depending on the specific hazard configuration in the relevant delta(s), the library provides guidance on which vulnerability indicators or proxies to take into account, while their site-specific weight can be evaluated through expert consultations. However, the library is open to extensions in the future and could also be adapted to different spatial scales and/or hazard configurations, such as earthquakes, tsunamis, etc. Underscoring the need to consider coastal river deltas as closely coupled human-environmental systems and providing a blueprint for future assessments of the vulnerability and risks faced by these systems that has been shaped in close collaboration with local stakeholders in the three case study deltas, the paper also responds to some of the fundamental research questions in sustainability science as reported by Kates (2011), e.g. on what determines the vulnerability of human-environment systems.

Despite these advantages, the GDRI and its application to the three case study deltas has several limitations which need to be addressed in future research. First, the index-based assessment is static in time, space as well as in regards to potentially non-linear linkages between SES indicators. For example it does not enable evaluating the effect of interventions in one administrative unit of a delta (e.g. in terms of infrastructure to control water, etc.) on risk levels in another location of the delta. Second, data for the indicators were drawn from different sources and for different years, with implications on the reliability of the results. The presented reliability index makes this weakness transparent. Third, data quality, data availability, the paucity of spatial (i.e. gridded) datasets, and the use of proxy indicators can be considered a limiting factor – particularly in data-scarce environments. By highlighting this limitation (Table 3), this paper also makes a call to governments for enhanced collection, management and provision of updated, reliable spatial data. This is fundamental if Priority 1 of the Sendai agreement ('Understanding disaster risk') is to be met with success. Although the GDRI is designed to pursue a spatial approach, the lack of spatially explicit, gridded data for many of the indicators that were considered in the analysis presents another limitation. While the exposure analysis enables planners to understand where within a delta people or ecosystems are located relative to hazard zones, the GDRI was constructed at administrative sub-delta scale and does not enable planners to make any inferences on vulnerability or risk of SES within these units. Fourth, an associated limitation is that while using sub-national administrative units for the communication of the results supports decentralized decision-making, the coarse resolution applied in this study (Amazon delta: municipal level; GBM delta: district level; Mekong delta: province level) does not capture potential urban-rural differences in disaster risk within these units. Fifth, the linear min-max normalization approach applied here, although most commonly used in index construction and vulnerability assessment (Beccari, 2016), presumes that for each unit increase between zero and one there is a proportional and corresponding increase in vulnerability which is often not the case. Using expert-defined thresholds and/or value functions for each indicator could help to at least partly overcome this issue – albeit introducing another layer of subjectivity and complexity in risk assessments. Sixth, the relevance of vulnerability indicators could vary spatially across and within deltas. While the GDRI has been principally designed to enable users to incorporate indicator weights (see Eq. (1)), equal weights were used for all indicators due to the lack of evidence on their location-specific relevance. Hagenlocher and Castro (2015) compared the impact of different weighting schemes, including weights based on regression coefficients, principal component analysis and equal weights in the context of a spatially explicit grid-based vulnerability and risk assessment and found no statistically significant impact of the weighting schemes. Nonetheless, going beyond the reliability metric presented here, follow-up research should analyze the sensitivity of the index to weighting choices. Lastly, the hierarchical design of the GDRI multiple aggregation steps for assessing multi-hazard SES vulnerability poses another challenge: the more times indicator scores are incrementally averaged, the less variability there is in the output scores.

To face the above challenges, attempts are currently underway to dynamize the GDRI using a Bayesian modeling approach and to further downscale the GDRI to the sub-municipal level for selected municipalities in the Amazon delta. This will also provide an opportunity to validate the findings against existing loss and damage information – a topic that has insufficiently been addressed to date. To test the transferability of the GDRI and its associated indicator library, as well as its concordance with other index-based approaches, an assessment of multi-hazard exposure, vulnerability and risk at the census tract level is currently ongoing for the Mississippi delta in the United States.

5. Conclusions

The aim of this paper is to present the development of a novel approach that can be used as a blueprint for spatial single- or multi-hazard risk assessments of closely coupled deltaic social-ecological systems at sub-delta scales and apply it to the Amazon, Ganges-Brahmaputra-Meghna, and Mekong deltas. Novelties include the introduction of a modular risk assessment approach that differentiates between hazard-dependent and independent vulnerability indicators, the introduction and piloting of an indicator library that can provide guidance for future assessments in river deltas, and the application of a social-ecological systems perspective in the assessment.

Findings from this study underscore the importance of not only considering societal vulnerabilities as a constituent of risk, but also including the ecological dimension more systematically when conducting risk assessments to inform disaster risk reduction and climate change adaptation planning and strategies – notably in places of strong social-ecological coupling such as coastal river deltas.

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Appendix A. Supplementary data

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References

Abson D.J., Dougill, A.J., Stringer, L.C., 2012. Using principal component analysis for information-rich socio-ecological vulnerability mapping in Southern Africa Applied Geography 35, 515-24.

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change 16, 268-281.

Asare-Kyei, D., Renaud, F.G., Kloos, J., Walz, Y., Rhyner, J., 2017. Development and validation of risk profiles of West African rural communities facing multiple natural hazards. PLoS ONE 12, e0171921.

Balica, S., Dinh, Q., Popescu, I., Vo, T.Q., Pham, D.Q., 2012. Flood impact in the Mekong delta, Vietnam. J. Maps 10, 257-268.

Beccari, B., 2016. A comparative analysis of disaster risk, vulnerability and resilience composite indicators. PLoS Currents, 8.

BEH, UNU-EHS, 2016. World Risk Report. Focus: Logistics and Infrastructure. Available from http://weltrisikobericht.de/wp-content/uploads/2016/08/WorldRiskReport2016.pdf. Accessed on 12 September 2017.

Bianchi, T.S., Allison, M.A., 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proc. Natl. Acad. Sci. 106, 8085-8092.

Birkmann, J., Garschagen, M., Tuan, V.V., Binh, N.T., 2012. Vulnerability, Coping and Adaptation to Water Related Hazards in the Vietnamese Mekong Delta. in: The Mekong Delta System: Interdisciplinary Analyses of a River Delta, (eds Renaud, F.G., Kuenzer, C. Springer, Netherlands), pp 245-289.

Birkmann, J., Cardona, O.D., Carreño, M.L., Barbat, A.H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., Welle, T., 2013. Framing vulnerability, risk and societal responses: the MOVE framework. Nat. Hazards 67, 193-211.

Blaikie, P., Cannon, T., Davis, I., Wisner, B., 1994. At risk. Natural Hazards, People's Vulnerability, and Disasters (Routledge, London, New York).

Bordi, I., Fraedrich, K., Petitta, M., Sutera, A., 2007. Extreme value analysis of wet and dry periods in Sicily. Theoretical and Applied Climatology 87, 61-71.

Brondizio, E.S., Vogt, N.D., Mansur, A.V., Anthony, E.J., Costa, S., Hetrick, S., 2016. A conceptual framework for analyzing deltas as coupled social-ecological systems: an example from the Amazon River Delta. Sust. Sci. 11, 591-609.

Burton, C.G., Cutter, S.L., 2008. Levee failures and social vulnerability in the Sacramento-San Joaquin delta area, California. Nat. Hazards Rev. 9, 136-149.

Campell, I.C., 2012. Biodiversity of the Mekong Delta. in: The Mekong Delta System: Interdisciplinary Analyses of a River Delta (eds. Renaud, F.G., Kuenzer, C., Springer Environmental Science and Engineering, Dordrecht), pp 293-313.

Chapman, A., Darby, S., 2016. Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. Sci. Total Environ. 559, 326-338.

Chen, W., Cutter, S.L., Emrich, C.T., Shi, P., 2013. Measuring social vulnerability to natural hazards in the Yangtze River delta region, China. Int. J. Disaster Risk Sci. 4, 169-181.

Coleman, J., Oscar, H., DeWitt, B., 2008. Wetland loss in world deltas. J. Coastal Res. 24, 1-14.

Day, J.W., Agboola, J., Chen, Z., D'Elia, C., Forbes, D.L., Giosan, L., Kemp, P., Künzer, C., Lane, R., Ramachandran, R., Syvitski, J., Yanez-Arancibia, A., 2016. Approaches to defining deltaic sustainability in the 21st century. Estuar Coast Shelf. Sci. 183, 1-17.

de Andrade, M.M.N., Szlafsztein, C.F., Souza-Filho, P.W.M., Araujo, A.D.R., Gomes, M.K.T., 2010. A socioeconomic and natural vulnerability index for oil spills in an Amazonian harbor: a case study using GIS and remote sensing. J. Environ. Manag. 91, 1972-1980.

De Lange, H.J., Sala, S., Vighi, M., Faber, J.H., 2010. Ecological vulnerability in risk assessment – A review and perspectives. Sci. Total Environ. 408, 3871-3879.

Dinh, Q., Balica, S., Popescu, I., Jonoski, A., 2012. Climate change impact on flood hazard, vulnerability and risk of the Long Xuyen quadrangle in the Mekong delta. J. of Maps 10, 103-120.

Eakin, H., Luers, L.L., 2006. Assessing the vulnerability of social-environmental systems. Annu. Rev. Environ. Resour. 31, 365-394.

Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006 Effective sea-level rise and deltas: Causes of change and human dimension implications, Glob. Planet Change 50, 63-82.

Few, R., Tran P.G., 2010. Climatic hazards, health risk and response in Vietnam: Case studies on social dimensions of vulnerability. Glob. Environ. Change 20, 529-538.

Fuchs, S., Birkmann, J., Glade, T., 2012. Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. Nat Hazards 64, 1696.

Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T., Marcomini, A., 2016. A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. J. Environ. Manag. 168, 123-132.

Giosan, L., Syvitski, J., Constantinescu, S., Day, J., 2014. Climate change: protect the world's deltas. Nature 516, 31-33.

Government of Vietnam & Dutch Government. 2013. Mekong Delta Plan. Available at: https://www.wur.nl/upload_mm/2/c/3/b5f2e669-cb48-4ed7-afb6-682f5216fe7d_mekong.pdf. Accessed on 12 September 2017.

Greiving, S., 2006. Integrated risk assessment of multi-hazards: a new methodology. in: Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, (ed Schmidt-Thomé, P.), pp 42, 75-82.

Hagenlocher, M., Castro, M.C., 2015. Mapping malaria risk and vulnerability in the United Republic of Tanzania: a spatial explicit model. Pop. Health Metrics 13, 2.

Hewitt, K., 1983. The idea of calamity in a technocratic age. in: Interpretations of Calamity from the Viewpoint of Human Ecology. The Risks & Hazards Series, (ed Hewitt, K. Allen & Unwin, Boston), pp. 3-32.

Higgins, S., 2016. Review: Advances in delta-subsidence research using satellite methods. Hydrogeol. J. 24, 587-600.

Hinkel, J. Lincke, D., Vafeidls, A., Parrette, M., Nicholls, R., Tol, R., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation cost under 21st sea-level rise. Proc. Natl. Acad. Sci. 111, 3292-3297.

Horton, B.P., Rahmstorf, S., Engelhart, S., Kemp, A., 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quat Sci Rev 84, 1-6.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (eds Field, C.B. et al., Cambridge University Press, Cambridge, UK, and New York, NY, USA).

IPCC, 2014. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Field et al. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).

Islam, M.N., Malak, M.A., Islam, M.N., 2013. Community-based disaster risk and vulnerability models of a coastal municipality in Bangladesh. Nat. Hazards 69, 2083-2103.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. Nat. Hazards 64, 1925-1958.

Kates, R.W., 2011. What kind of a science is sustainability science? Proc. Natl. Acad. Sci. 108, 19449-19450.

Kienberger, S., Hagenlocher, M., Delmelle, E., Casas, I., A., 2013. WebGIS tool for visualizing and exploring socioeconomic vulnerability to dengue fever in Cali, Colombia. Geospat. Health 8, 313-316.

Kuenzer, C., Ottinger, M., Lie, G., Sun, B., Dech, S., 2014. Earth observation-based coastal zone monitoring of the Yellow river delta: dynamics in China's second largest oil producing region over four decades. Appl. Geogr. 55, 72-107.

Lázár, A.N., Clarke, D., Adams, H., Razzaque, A., Szabo, S., Nicholls, R.J., Matthews, Z., Begum, D., Saleh, A.F.M., Abedin, M.d.A., Payo, A., Streatfield, P.K., Hutton, C., Mondal, M.S., Moslehuddin, A.Z.M.d., 2015. Agricultural livelihoods in coastal Bangladesh under climate and environmental change – a model framework. Environm. Sci.: Processes & Impacts 17, 1018-1031.

Lewis, J. (1999). Development in disaster-prone places: studies of vulnerability. Intermediate Technology Publications, London.

Liu, B., Siu, Y.L., Mitchell, G., Xu, W., 2013. Exceedance probability of multiple natural hazards: risk assessment in China's Yangtze River delta. Nat. Hazards 69, 2039-2055.

Mansur, A.V., Brondizio, E.S., Roy, S., Hetrick, S., Vogt, N., Newton, A., 2016. An assessment of urban vulnerability in the Amazon delta and estuary: a multi-criterion index of flood exposure, socio-economic conditions and infrastructure. Sust. Sci. 11, 625-643.

Mondal, D., 2013. Assessing social vulnerability to coastal hazards: An examination on Sagar Island of Sundarban delta. Res. J. Humanities Soc. Sci. 4, 210-215.

OECD, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. Available at: https://www.oecd.org/std/42495745.pdf. Accessed on 12 September 2017.

O'Keefe, P., Westgate, K., Wisner, B., 1976. Taking the naturalness out of natural disasters. Nature 20, 566-567.

Pennington, B., Bunbury, J., Hovlus, N., 2016. Emergence of civilization, changes in fluvio-deltaic style, and nutrient redistribution forced by holocene sea-level rise. Geoarchaeology 31, 194-210.

Renaud, F.G., Syvitski, J.P.M., Sebesvari, Z., Werners, S.E., Kremers, H., Kuenzer, C., Ramesh, R., Jeukens, A., 2013. Friedrich J Tipping from the Holocene to the Anthropocene: How threatened are major world deltas? Curr. Opin. Environ. Sustain. 5, 644-654.

Sebesvari, Z., Foufoula-Georgiou, E., Harrison, I., Brondizio, E., Bucx, T., Dearing, J.A., Ganguly, D., Ghosh, T., Goodbred, S.L., Hagenlocher, M., Hajra, R., Kuenzer, C., Mansur, A.V., Matthews, Z., Nicholls, R.J., Nilsen, K., Overeem, I., Ramachandran, P., Rahman, M.M.d., Ramachandran, R., Renaud, F.G., Robin, R.S., Subba, R., Bonthu, S., Gulab, Szabo, S., Tessler, Z., van de Guchte, C., Vogt, J., Wilson, C.A., 2016a. Imperatives for sustainable delta futures. Brief for GSDR. Sustainable Development Knowledge Platform. Available from https://sustainabledevelopment.un.org/content/documents/972032_Sebesvari_Imperatives%20for%20sustainable%20delta%20futures.pdf. Accessed on 12 September 2017.

Sebesvari, Z., Renaud, F.G., Haas, S., Tessler, Z., Hagenlocher, M., Kloos, J., Szabo, S., Tejedor, A., Kuenzer, C., 2016b. A review of vulnerability indicators for deltaic social–ecological systems. Sust. Sci. 11, 575-590.

Steckler, M.S., Akhter, S.H., Seeber, L., 2008. Collision of the Ganges–Brahmaputra Delta with the Burma Arc: Implications for earthquake hazard. Earth and Planetary Science Letters 273, 367-378.

Syvitski, J., Kettner, A., Overeem, I., Hutton, E., Hannon, M., Brakenridge, G., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nichols, R., 2009. Sinking deltas due to human activities. Nat Geosci 2, 681-686.

Szabo, S. et al. Making SDGs work for climate change hotspots. Environment: Science and Policy for Sustainable Development 58, 24-33 (2016a).

Szabo, S., Nicholls, R.J., Neumann, B., Renaud, F.G., Matthews, Z., Sebesvari, Z., Agha Kouchak, A., Bales, R., Warren, C., Ruktanonchai, Kloos, J., Foufoula-Georgiou, E., Wester, P., New, M., Rhyner, J., Hutton, C., 2016b. Population dynamics, delta vulnerability and environmental change: comparison of the Mekong, Ganges-Brahmaputra and Amazonas delta regions. Sust. Sci. 11, 539-554.

Tessler, Z.D., Vörösmarty, C.J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J.P.M., Foufoula-Georgiou, E., 2015. Profiling risk and sustainability in coastal deltas of the world. Science 349, 638-643.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. 100, 8074-8079.

Wannewitz, S., Hagenlocher, M., Garschagen, G., 2016. Development and validation of a sub-national multi-hazard risk index for the Philippines. GI_Forum – J. Geographic Inf. Sci. 1, 133-140.

White, G., 1973. Natural hazards research. in: Directions in Geography ed Chorley, R.J., (ed Methuen, London), pp. 193-216.

Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2004. At risk. Natural Hazards, People's Vulnerability, and Disasters. 2nd ed. (Routledge, London, New York).

Wolters, M., Kuenzer, C., 2015. Vulnerability assessments of coastal river deltas – categorization and review. J. Coastal Cons. 19, 345-368.

Wolters, M., Sun, Z., Huang, C., Kuenzer, C., 2016. Environmental awareness and vulnerability in the Yellow River delta: results based on a comprehensive household survey. Ocean Coast. Management 120, 1-10.

UNISDR (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. Available from http://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf. Accessed on 12 September 2017.