Sustain Sci
DOI 10.1007/s11625-016-0366-4

SPECIAL FEATURE: REVIEW ARTICLE

Sustainable Deltas: Livelihoods, Ecosystem Services, and Policy Implications

A review of vulnerability indicators for deltaic social–ecological systems

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Received: 31 July 2015 / Accepted: 20 April 2016

Abstract The sustainability of deltas worldwide is under threat due to the consequences of global environmental change (including climate change) and human interventions in deltaic landscapes. Understanding these systems is becoming increasingly important to assess threats to and opportunities for long-term sustainable development. Here, we propose a simplified, yet inclusive social–ecological system (SES)-centered risk and vulnerability framework and a list of indicators proven to be useful in past delta assessments. In total, 236 indicators were identified through a structured review of peer-reviewed literature performed for three globally relevant deltas—the Mekong, the Ganges–Brahmaputra–Meghna and the Amazon. These are meant to serve as a preliminary "library" of potential indicators to be used for future vulnerability assessments. Based on the reviewed studies, we identified disparities in the availability of indicators to populate some of the vulnerability domains of the proposed framework, as comprehensive social–ecological assessments were seldom implemented in the past. Even in assessments explicitly aiming to capture both the social and the ecological system, there were many more indicators for social susceptibility and coping/adaptive capacities as compared to those relevant for characterizing ecosystem susceptibility or robustness. Moreover, there is a lack of multi-hazard approaches accounting for the specific vulnerability profile of sub-delta areas. We advocate for more comprehensive, truly social–ecological assessments which respond to multi-hazard settings and recognize within-delta differences in vulnerability and risk. Such assessments could make use of the proposed framework and list of indicators as a starting point and amend it with new indicators that would allow capturing the complexity as well as the multi-hazard exposure in a typical delta SES.

Handled by Zoe Matthews, University of Southampton, Southampton, United Kingdom.

Electronic supplementary material The online version of this article (doi:10.1007/s11625-016-0366-4) contains supplementary material, which is available to authorized users.

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Keywords Sustainable deltas · Social–ecological systems · Vulnerability assessment frameworks · Indicators · Multiple hazards

Introduction

Coastal deltas are dynamic low-lying areas resulting from the interaction between the river(s) forming the delta, upstream catchment areas and receiving oceans (Kuenzer and Renaud 2012). Deltas are typically hot spots of biodiversity. They provide ample natural resources such as water and fertile soils, and therefore are often areas with intensive agricultural production and high population densities (Ericson et al. 2006). At the same time, they are often highly vulnerable to environmental hazards such as floods, droughts, hurricanes, storm surges, sea-level rise and salinity intrusion (e.g., Dasgupta et al. 2011; Syvitski et al. 2009; Wong et al. 2014; Szabo et al. 2015a). Although the importance of socioeconomic change is increasingly acknowledged as a driver for delta vulnerability, in a review of coastal vulnerability assessments, Nicholls et al. (2008) concluded that coastal vulnerability assessments tended to focus on climate change in general and on sea-level rise in particular. Torresan et al. (2008) further highlighted the lack of comprehensive and site-specific vulnerability assessments which could support adaptation planning at the regional scale. With many deltas globally at risk (Syvitski 2008; Ericson et al. 2006; Kuenzer and Renaud 2012; Tessler et al., 2015), there have been recent calls for a global delta sustainability initiative[1] (Foufoula-Georgiou et al. 2013) and for a science-based global strategy for protecting deltas (Giosan et al. 2014), among others. All three major global processes of 2015 including the Sendai Framework for Disaster Risk Reduction (SFDRR, UN 2015a), the Sustainable Development Goals (SDGs, UN 2015b) as well as the Paris Agreement on climate change (UN 2015c), provide entry points to tackle challenges relevant to deltaic systems. As an example, the SDG target 1.5 aims to "build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters" by 2030 (UN 2015b:15). To be able to assess and monitor progress toward these agreements, vulnerable elements of the deltás social–ecological system (SES) need to be identified. While a large number of vulnerability assessments exist for coastal regions in general and delta environments in particular, the development of unified frameworks and indicators at the global scale is critical (Tessler et al. 2015). It then becomes relevant to determine if important factors that shape these vulnerabilities can be identified for deltas globally and if a common vulnerability assessment approach for delta regions can be devised. To address these issues, the objectives of this paper are therefore to (1) propose a multi-hazard risk and vulnerability assessment framework suitable for delta assessments based on a review of existing frameworks; (2) perform a systematic review of indicators used in delta vulnerability assessments by focusing on three globally relevant deltas; (3) initially populate the framework with indicators used in delta assessments to identify the level of availability of such indicators; and (4) discuss the strength and weaknesses of available sets of indicators to support the ongoing development of a vulnerability index that can be applied across deltas globally.

[1] This call has led the International Council for Science (ICSU) to endorse the Sustainable Deltas 2015 initiative.

Systematic review of vulnerability indicators used in assessments in three model deltas

Peer-reviewed studies included in this review were selected from the Thomson Reuters Web of Science database.[2] The review focused on three major deltas with global relevance and different social and ecological conditions as well as hazard and risk patterns (see also Szabo et al. 2015a, Tessler et al. 2015, this special issue): the Mekong (MKD), the Ganges–Brahmaputra–Megna (GBM), and the Amazon deltas. In mainly physical impact-based risk assessments, the MKD and the GBM have been classified as extremely vulnerable based on the number of people potentially displaced by current estimates of sea-level rise trends to 2050 (Ericson et al. 2006) and as "deltas in peril" due to a great reduction in aggradation combined with accelerated compaction which are higher than the actual rates of global sea-level rise (Syvitski et al. 2009). These two deltas were selected to represent regions which are at high risk, are densely populated and where future development could be threatened. It was also hypothesized that in these deltas, vulnerability assessments had been undertaken by various research groups allowing the identification of a large number of vulnerability indicators. The Amazon Delta was selected as it was classified by Ericson et al. (2006) as having medium vulnerability and by Syvitski et al. (2009) as a delta not at risk with respect to flooding, but this delta is also seeing rapid development changes. The expectation was that the review would result in fewer indicators for the Amazon when compared with the other two deltas, allowing for a discussion on the state of the art in terms of vulnerability assessment for a range of deltas facing different challenges.

Search criteria included "geomorphic" terms related to coastal river deltas ("delta* OR estuary* OR coast* OR shore*"), "assessment" terms to identify research associated with risk assessment ("risk OR vulner* OR resil*", and "eval* OR assess* OR profile OR index OR indic*"), and "geographic" terms identifying case study locations ("Bangladesh OR Ganges OR Brahmaputra OR Amazon OR Mekong"). The geographic category was constructed to exclude studies cast at the country scale ("Vietnam") in preferences for those cast at the delta scale ("Mekong"). The country-level name "Bangladesh" was included, as the majority of the country is within the boundaries of the GBM delta. There was no restriction regarding the year of the study or publication.

[2] www.webofknowledge.com.

The first and broadest search, using only the geomorphic and assessment categories across abstracts, produced 13,823 results. The second search additionally required the geomorphic terms to appear in the title, resulting in 3431 results. The third and most focused search incorporated the geographic terms in titles or abstracts, returning 93 publications (by end of 2014). These 93 publications were screened by two researchers independently to identify thematically irrelevant papers (dealing, e.g., with antibiotic resistance in catfish). Fifty-five papers were finally selected for a structured review. A list of reviewed documents is provided in Table S1.

In the review process, the following information was systematically extracted from the studies:

1. General parameters: delta(s) considered, time of the assessment, study aim, end products, main results;
2. Methodological characteristics: specific hazard considered framework used, indicators used per vulnerability domain, type, source and scale of data.

General overview of assessments in the three reviewed deltas

The majority (82 %) of the reviewed papers referred to studies conducted after 2000. 68 % of the papers were published in 2010 or later. Twenty-two publications focused entirely or partially on the MKD, 21 on the GBM and three on the Amazon indicating that the Amazon has received less attention likely due to its lower risk profile to date, as originally hypothesized (e.g., Tessler et al. 2015). The papers considered different hazards, including: environmental pollution ($n = 8$), sea-level rise ($n = 6$), flooding ($n = 6$), waterborne diseases ($n = 6$), (natural) arsenic contamination ($n = 5$), and coastline erosion ($n = 4$), and thus covered for a broader range of hazards than observed earlier by Nicholls et al. (2008). The goal of the studies varied, with contribution to adaptation and comparative assessments being two of the more often stated reasons for the studies. Both, natural and anthropogenic hazards were considered in the papers, but with a focus on natural hazards. Mixed-method approaches (combining qualitative and quantitative methods) gained importance in more recent years with all of the 12 relevant papers being published in 2009 or later. The same trend can be observed for papers considering both social and ecological systems (called SES-type papers thereafter). Three scales (local, sub-delta, and delta) were represented with small-scale studies being predominant (47 %), followed by sub-delta-scale studies (22 %). Studies undertaken at the sub-delta scale provided spatially disaggregated information in reference to different hazards or different components of the SES on a regional scale. For example, the rates of coastline change were evaluated for different sections of the coastal area of GBM by Sarwar and Woodroffe (2013), and flood risk was evaluated for different landform units within the Mekong delta by Haruyama and Shida (2008). None of the studies considered multiple scales or cross-scale effects. The lack of studies considering more than one scale is in line with observations from Wolters and Kuenzer (2015). A table summarizing the aim of the assessments, approaches, and methods used is provided in Table S2.

Vulnerability assessment of social–ecological systems: a proposed framework for deltas

General vulnerability assessment frameworks

Birkmann (2013) provided an overview of vulnerability assessment frameworks. For vulnerability assessment of SES in sustainability science, the SUST (Turner et al. 2003) is a particularly influential framework which integrates elements from risk/hazard approaches to vulnerability as well as ecological resilience theory into a multi-scale model of vulnerability of SES. Vulnerability, in this framework, is understood as a result of an interaction of multiple biophysical and human processes, stresses, and shocks, which may respond nonlinearly and dynamically with multiple feedbacks across scales. For a practical vulnerability assessment of the SES to floods, Damm (2010) modified the SUST framework by explicitly differentiating between the susceptibility of the social and the ecological systems, replacing resilience with capacities, and dividing the latter into robustness of the ecosystem and coping and adaptive capacities of the social system. The MOVE framework (Birkmann et al. 2013) is a risk assessment framework which considers vulnerability, resilience, coping, and adaptation. Vulnerability is mainly linked to societal conditions and processes, but interactions and coupling processes between the environment and the social system are acknowledged.

While vulnerability is often assessed in a hazard-specific manner, multi-hazard approaches are gaining importance, acknowledging that an SES is often exposed to more than one hazard. Recently, Kloos et al. (2015) developed a multi-hazard risk assessment framework explicitly looking at the potential impacts of single and multiple hazards affecting SES. Garschagen (2014) integrated framework for vulnerability and adaptation analysis explicitly and considers natural and anthropogenic hazards in the context of environmental and climatic change as well as socioeconomic change and transformation processes.

In this special issue, Mansur et al. (2016) published a conceptual model of vulnerability specifically for the urban areas of the Amazon Delta and Estuary. The model considers the social–ecological system as the unit of analysis and focuses on the social vulnerability in urban areas as the target of the analysis, while considering also impacts on ecosystem services. The model was applied in the context of flood risk Mansur et al. (2016).

Indicators are frequently used to assess vulnerability (Eriksen and Kelly 2006). Many methods are available for indicator-based vulnerability assessments, ranging from global or national assessments (e.g., Peduzzi et al. 2009; UNDP/BCPR 2004), including the Disaster Risk Hotspots (Dilley et al. 2005), the Global Risk Analysis (UN 2009, 2011, 2013), and the World Risk Index (Birkmann et al. 2014) to participatory assessments at the local level (e.g., Bollin and Hidajat 2006; Asare-Kyei et al. 2015).

From the 55 reviewed papers, very few used conceptual frameworks as basis for the assessment (e.g., Balica et al. 2012; Swapan and Gavin 2011). A noteworthy exception is the framework used by Balica et al. (2012) to develop a flood vulnerability index for coastal cities which has the most similarities with the above-described SES frameworks. Possibly, available SES frameworks provide too little guidance for their application in the context of real-world assessments. Instead, indicator-based approaches without explicitly using an overarching framework seem to be more often applied (e.g., Composite Vulnerability Index (CVI) by de Andrade et al. 2010 or the "Water Needs Index" (WNI) by Moglia et al. 2012). Other papers did not refer to a specific framework or index approach, but used a wide range of methodologies mostly to assess selected aspects of vulnerability either of the social, institutional, economic or the physical and ecological components of the system (e.g., Haruyama and Shida 2008; Lara et al. 2009; Collins 2003; Dang et al. 2011).

Proposed Delta-SES vulnerability assessment framework

For the purpose of delta vulnerability assessments and based on the previously described frameworks, we propose the Delta-SES framework, a simplified yet inclusive framework for multi-hazard SES risk and vulnerability assessment (Fig. 1).

The Delta-SES framework aims to synthesize key, relevant elements of the previously mentioned frameworks by:

1. focusing on the SES and acknowledging different spatial scales (Turner et al. 2003), here from sub-delta to basin scale for the ecosystem and from districts/provinces to countries or river basin organizations (RBOs) for the social system.
2. considering ecosystem robustness as one of the sub-domains (Damm 2010);
3. referring explicitly to multi-hazard settings and acknowledging possible tipping and transformation processes (Kloos et al. 2015) and
4. considering not only natural, but also anthropogenic hazards (IPCC 2012, Garschagen 2014).

In the Delta-SES framework, the social and ecological sub-systems intersect each other by, e.g., impacts of human activities on the environment and the provision of services by ecosystems (MA 2005), and are characterized by interactions and feedbacks at various temporal and spatial scales. Although all scales are relevant and interact with each other, the essential place of the analysis is considered to be the sub-delta scale to account for the differences in vulnerability among delta sub-regions, e.g., coastal zones, floodplains, and urban areas, and the fact that different parts of a delta can be predominantly affected by different hazards. Several natural and/or anthropogenic hazards might occur at the same place, leading to interactions among hazards and impacts and/or to cascading events or impacts (Fig. 1).

The nature and magnitude of the hazard(s) as well as the vulnerability of the SES determines the impacts experienced by the SES and its sub-systems and also the risk to experience harm. Hazards might originate within a given SES (e.g., water pollution), but can also be generated outside the SES (e.g., global sea-level rise). These interactions from outside as well as SES-internal processes might lead to transformations and tipping processes, which greatly influence the vulnerability context (Fig. 1). For the definitions of the major framework elements, see Table S3.

In the present paper, the proposed Delta-SES framework provided a structure, so that all indicators identified in the reviewed papers could be included in the respective vulnerability domains. Individual indicators were classified into four different vulnerability domains: ecosystem susceptibility, social susceptibility, ecosystem robustness, and coping/adaptive capacities of the social system. Relevant abiotic features (e.g., wind, waves) were classified as part of the ecosystem for the purpose of this review. Indicators within each vulnerability domain were further assigned to sub-categories aligned with the categories (e.g., key economic sectors and services, human health, and human security) used by AR5 Working Group II: Impacts, Adaptation and Vulnerability (IPCC 2014). In doing so, the review populated the framework with indicators which provide the basis for the analysis of the strength and weaknesses of existing indicators for an SES-based delta assessment. In the future, the framework can: guide the assessment of vulnerability in deltas in terms of identifying

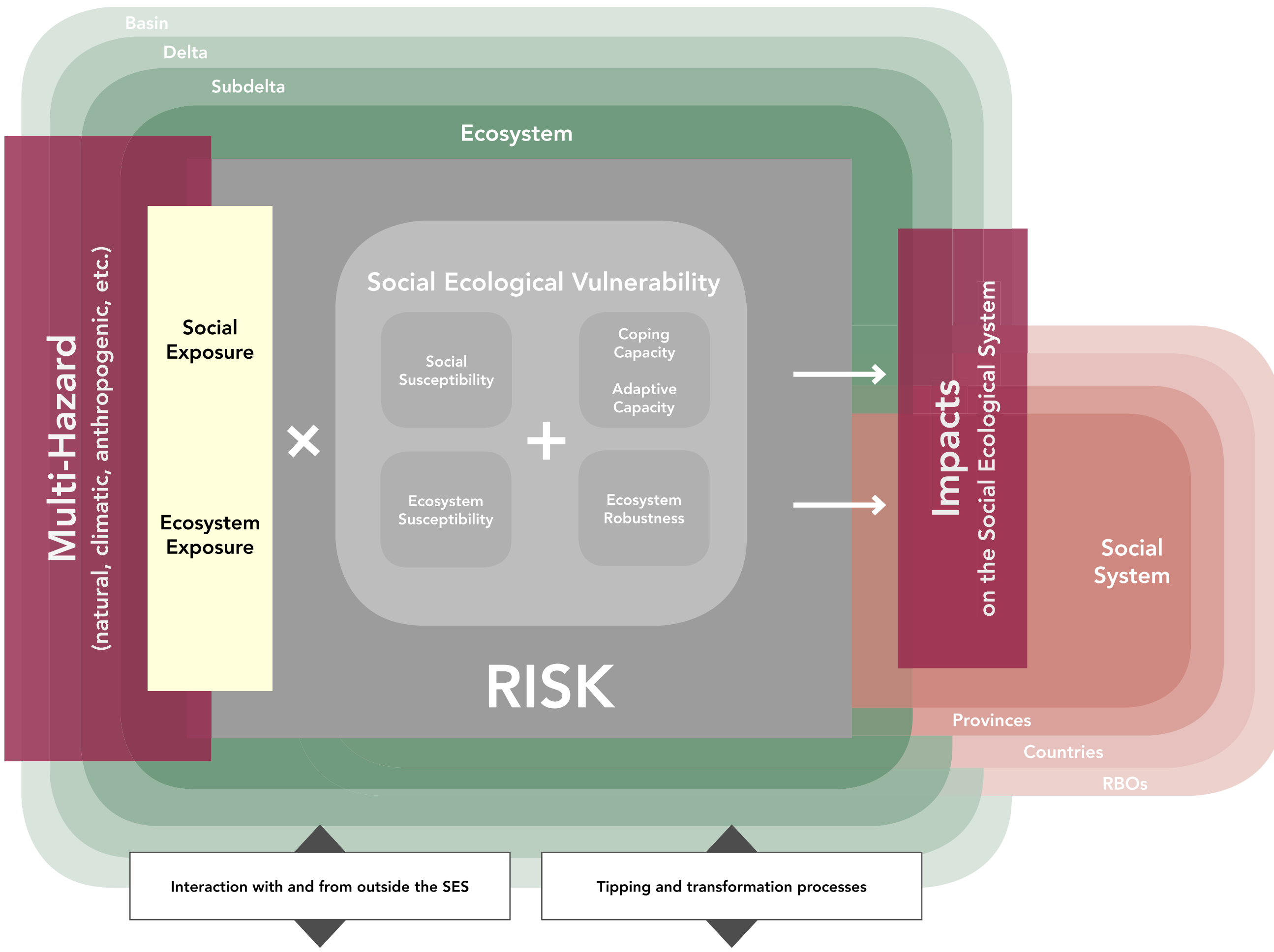


Fig. 1 Deltas-SES framework (source: authors based on Turner et al. 2003; Damm 2010; Garschagen 2014; Kloos et al. 2015)

appropriate indicators for the different domains and combining these in a meaningful index; and foster the reproducibility/transferability of the vulnerability assessment to different delta regions. Therefore, the indicators listed below should be seen as a "library" of indicators, which needs to be complemented through further research and adapted to the local delta idiosyncrasies, but on which experts can draw on, using scientific reasoning, when carrying future delta vulnerability assessments.

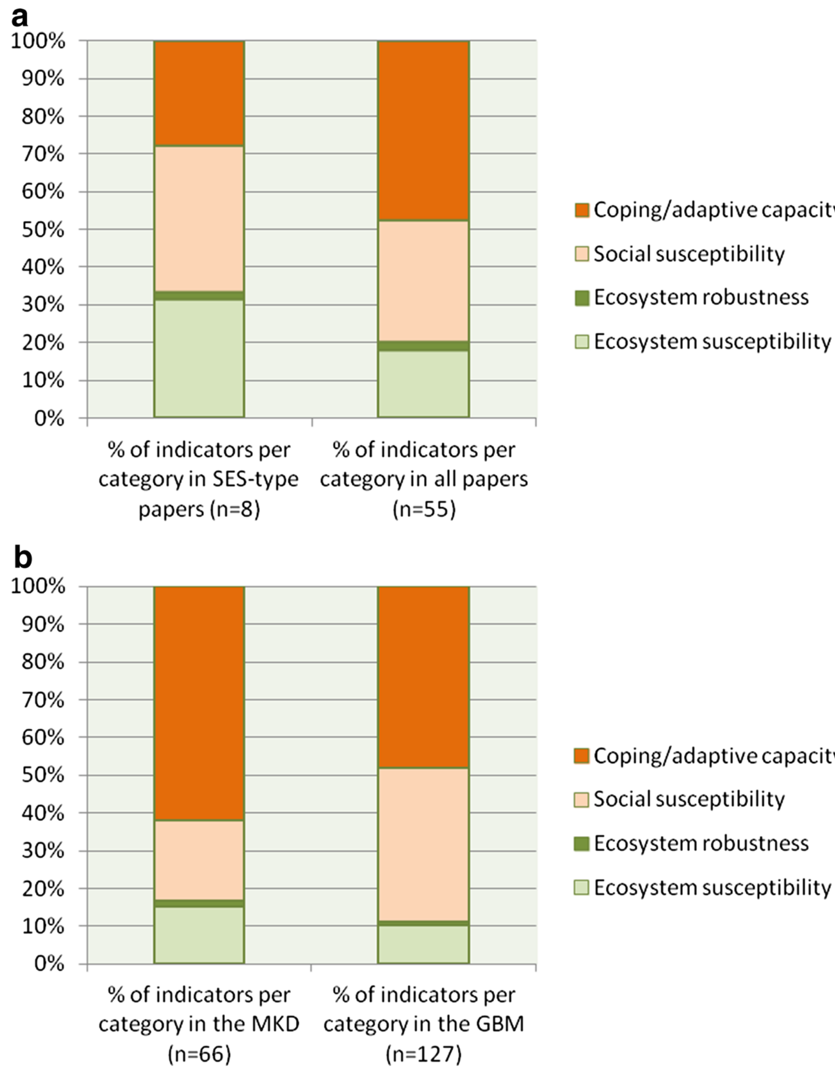
Assessment of indicators used in the reviewed papers

Quantitative overview of individual indicators used

236 different indicators were identified during the review characterizing the six sub-domains of vulnerability as described in the Delta-SES framework. Supplementary material Table S4 provides the complete list of indicators. The review yielded a greater number of indicators for the characterization of the vulnerability of the social system (84 % of all identified indicators) than for the assessment of ecosystem vulnerability. This is partially related to the relatively greater number of papers dealing with social vulnerability, but the pattern also prevails to a lesser extent in SES-type papers (Table S5).

Among the four vulnerability domains (Fig. 1), indicators for coping and adaptive capacity and social susceptibility have been used most often, while indicators of ecosystem susceptibility and robustness are under-represented even in SES-type studies (Fig. 2a). Ecosystem-related indicators were rarely used in both the Mekong and the Ganges–Brahmaputra–Meghna delta. Therefore, for a balanced SES-assessment, efforts to develop and use suitable indicators for the assessment of ecosystem susceptibility and robustness need to be enhanced.

Fig. 2 **a** Comparison of the share of indicators dealing with the four vulnerability domains in SES-type papers vs. all reviewed papers. **b** Comparison of the share of indicators dealing with the four vulnerability domains in the papers related to the Mekong Delta (MKD) and Ganges–Brahmaputra–Meghna Delta (GBM)



Qualitative assessment of indicators used

Model deltas: overview of indicators used in the reviewed papers

In the MKD, the hazards most considered in the reviewed papers were environmental pollution (6 papers), sea-level rise (5 papers), (natural) arsenic contamination (4 papers), and health-related hazards (3 papers).

Social susceptibility was assessed by indicators related to livelihoods (3 indicators, 2 papers) and practices causing or preventing the spread of waterborne diseases (10 indicators, 3 papers). Only one study used an indicator related to ecosystem robustness. Adaptive capacity was mainly represented by indicators related to social adaptation options (26 indicators, 4 papers), whereas indicators related to individual behavior were the most important (23 indicators, 3 papers). Additionally, indicators for structural and physical adaptive capacity were abundant (13 indicators, 5 papers). Overall, the assessment indicators reflect well the threat posed by water pollution to the MKD (Sebesvari et al. 2012) and the fact that it is a very intensively cultivated delta with a relatively low degree of urbanization. Interestingly, however, aquaculture-related vulnerabilities were not extensively addressed, despite its relevance to the region.

In the GBM Delta, the most considered hazards were cyclones and storms (8 papers), (natural) arsenic contamination (3 papers), coastline retreat (3 papers), and flooding (3 papers). Similarly to the MKD, social susceptibility was mainly assessed by considering livelihoods (24 indicators, 8 papers) and health-related indicators (17 indicators, 5 papers). Ecosystem susceptibility was mainly assessed with indicators related to aquatic ecosystems (6 indicators, 3 papers) by referring to habitat degradation and water quantity and quality issues. One study considered biodiversity as an indicator for ecosystem robustness. Coping and adaptive capacity was mainly related to social adaptation options: (29 indicators, 7 papers) educational options being dominant (19 indicators, 7 papers). Similarly to the MKD, structural and physical adaptation options played the second largest role (22 indicators, 6 papers).

For the Amazon Delta, a low number of studies were retrieved by the structured search. The low number of available studies shows that the Amazon is not (yet) in the focus of vulnerability studies, as it is not considered to be widely at high risk. The three studies reviewed considered environmental pollution, waterborne diseases, and coastline retreat as hazards. Ecosystem susceptibility was related mainly to abiotic factors such as geomorphological features of the areas and oceanic wave characteristics. Similarly to the MKD and the GBM, livelihood-related indicators dominated social susceptibility assessments, while fish-based multimetric indices were used to characterize ecosystem robustness. Coping and adaptation indicators were rare and referred to structural and physical adaptation options (2 indicators, 1 paper) or to social (educational) options (1 indicator, 1 paper).

Overlapping indicators among the three deltas

To develop a set of relevant indicators to populate the Delta-SES framework, the indicators recorded in the reviewed papers were assessed to identify common patterns among deltaic regions. In a first step, indicators which were used in exactly the same manner in more than one delta were extracted. Overlapping indicators mainly described social susceptibility and adaptive capacity. For social susceptibility, the following indicators were used in more than one delta: income, share of population of working age (%), age (year), and size of landholdings (ha). For adaptation, the only overlapping indicator was the number of livelihood streams. Although few indicators overlapped, a closer look at the list of indicators (Table S4) revealed a large degree of similarities, with different indicator formulations being used to point to similar characteristics of an SES. This means that single studies might have used different indicators, but many of them are clustered in categories which could be used for standardized assessments in the future. The clusters are discussed in the next section.

Indicators related to ecosystem vulnerability

A full list of the indicators used in the papers is provided in Table S4 in the supplementary material. Table 1 shows a selection of indicators aiming to provide one illustrative example for each indicator category. The indicators address four main ecosystem types in the context of ecosystem susceptibility: aquatic ecosystems (natural and aquaculture) and terrestrial ecosystems (natural and agro-ecosystems). In general, the susceptibility of an ecosystem is influenced by the status and dynamics of the habitat (destruction, degradation, and fragmentation) as well as its biodiversity status. For terrestrial ecosystems, for example, different land cover types vary in terms of their susceptibility to saltwater intrusion; vegetation with shallow roots cannot withstand storms or erosion. The susceptibility of agro-ecosystems is determined, e.g., by the crop varieties, and the time and length of the growing season. These characteristics influence the impact of different hazards on yield and crop quality (e.g., indicators used by Nguyen et al. 2012). While destruction and degradation were considered to some extent, indicators referring to habitat fragmentation and biodiversity were missing in the assessments.

The susceptibility of natural aquatic ecosystems involved indicators belonging to three different dimensions: habitat destruction, degradation (declining water quality, often in context of favorable conditions for waterborne diseases), and changing water quantity. Concerning habitat destruction, changes in the extent of mangrove and wetland areas have often been studied in general as well as in delta-specific papers (e.g., by Shearman et al. 2013), indicating that this form of habitat degradation is of serious cross-delta concern. Water quality was assessed, e.g., by water temperature, pH, turbidity, and salinity of aquatic reservoirs and estuaries (e.g., Collins 2003; Lara et al. 2009), while water quantity was assessed, e.g., by the monthly inflow to a reservoir under different climate scenarios (m^3) (Mondal and Wasimi 2007). Surprisingly for these deltaic systems, only few studies dealt with the susceptibility of aquaculture, the decline in pond productivity being the main indicator used (e.g., Swapan and Gavin 2011).

The susceptibility of an ecosystem also depends on factors related to abiotic parameters such as geologic, geomorphologic, and oceanographic factors. The review showed that indicators such as the extent of land subsidence (mm/year) (e.g., Balica et al. 2012), the slope of the coast (degrees) (e.g., Vermaat and Eleveld 2012), the tidal pattern and wave climate (e.g., Oliveira et al. 2011), as well as sediment supply (Pruszak et al. 2002) were relevant in assessments. The review result is also supported by other papers which recognize land subsidence as highly relevant for the vulnerability of deltas to flooding worldwide in combination with sediment trapping in reservoirs upstream and sea-level rise (Syvitski et al. 2009). Torresan et al. (2012) provided a number of vulnerability indicators related to abiotic factors such as coastal slope, sediment budget, dunes, and mouth typology when assessing coastal vulnerability to sea-level rise inundation, storm surge flooding, and coastal erosion in the coastal area of the North Adriatic Sea.

The robustness of deltaic ecosystems has been rarely evaluated. Viana et al. (2012), for example, used fish-based

Table 1 Illustrative example indicators used or suggested by the reviewed papers for ecosystem vulnerability assessments

	Indicators
Ecosystem susceptibility	
Aquatic ecosystem	
Habitat destruction	Net increase/decrease in mangrove area (%)
Water quantity	Volume of water storage in the reservoir for different climate scenarios (m3)
Water quality	Salinity of the water of the aquatic reservoir (g/l)
Aquacultural ecosystem	
Pond aquaculture	Pond productivity (fry or fish/ha)
Terrestrial ecosystem	
Lan duse change	Percentage of change in major land use categories (%)
Agroecosystem	
Cropping system	Rice variety of land use class (Jasmine85/OM1940/IR50404/HD1/OM2514/etc.) (categorical)
Abiotic sphere	
Geology	Subsidence (mm/year)
Geomorphology	Coastal slope (deg)
Tidal patterns and wave climate	Maximal speed of tidal currents (m/s)
Fluvial suspension supply	Mean accumulation rate (cm/year)
Ecosystem robustness	
Aquatic ecosystem	
Fish-based multimetric indices	Estuarine biotic integrity index (EBI) (−)
Terrestrial ecosystem	
Habitat destruction	Percentage of vegetation loss (%)
Agroecosystem	
Farm management strategies	Percentage of farmer-managed populations of rice varieties grown (vs. Genebank conserved) (%)

Please refer to Table S4 for the full list of indicators as well as for the references. Note that indicators might point to positive or negative features of vulnerability and in some cases might also differ by hazards

metrics such as abundance biomass comparison (abc); biological health index; estuarine fish community, transitional fish classification, and estuarine biotic integrity.

Indicators related to social vulnerability

A full list of the indicators used in the papers is provided in Table S4 in the supplementary material. Table 2 shows a selection of indicators aiming to provide one illustrative example for each indicator category. For the purpose of this review, the indicators for social susceptibility were clustered into five categories (livelihoods and poverty, human health, key economic sectors and services, human security, and urban areas), following the structure used in IPCC (2014). The reviewed papers offered a broad range of indicators addressing livelihood susceptibility and poverty. Indicators related to income (e.g., Dang et al. 2011), the ability to generate income influenced by disability, age structure, and gender (e.g., Balica et al. 2012; Islam et al. 2014a) assets (e.g., Saroar and Routray 2011), and dependency on climate-sensitive livelihood sources such as aquaculture and agriculture (see, e.g., Paul et al. 2012) were frequently used. Indicators related to human health addressing, e.g., health impacts of storms and floods (e.g., Mallick et al. 2011), food and waterborne diseases, and arsenic contamination were used frequently (e.g., Chatterjee et al. 2010). Hygienic practices (e.g., Herbst et al. 2009; Few et al. 2013) as well as the quantity of consumed total arsenic via drinking water and rice consumption (Chatterjee et al. 2010) were important factors considered in studies whenever referring to the above-mentioned health threats. This is certainly driven by the fact that the population of the GBM—and to a lesser extent also the MKD—is highly exposed to arsenic-contaminated groundwater as well as to polluted surface water. High temperatures combined with low coverage rate of improved sanitation further exacerbate the prevalence of waterborne diseases. The use of a great number of related indicators is thus meaningful.

Regarding key economic sectors and services, the reviewed papers mainly focused on water and energy supply, transportation infrastructure, and construction and housing, which have clear implications for the susceptibility of the SES. For example, the capacity of the water supply system to continue delivering services during and in

Table 2 Illustrative example indicators used or suggested by the reviewed papers for social vulnerability assessment

Social susceptibility	Indicator
Urban areas	
Urbanization, population density, and population growth	Population density (n/km2)
Key economic sectors and services	
Aggregate measures of public infrastructure	Density of public infrastructure (m/ha)
Water supply	Volume of water storage in the reservoir (m3)
Transportation infrastructure	Roads (km)
Housing/settlement characteristics	Quality of house (categorical)
Livelihoods	
Income	Income (amount of money/household/year)
Disability	Percentage of disabled persons (%)
Age	Age (years)
Gender	Percentage of male-headed household (%)
Household size	Homestead/household size (number of persons)
Assets	Landholdings (ha)
Dependency on climate-sensitive income sources	Percentage of population primarily living on fishing (%)
Human security	
Land conflicts	Land conflicts per year (n)
Human health	
Health impacts due to storms and floods	Percentage of population with access to cyclone shelter/primary school (%)
Food and waterborne diseases	Percentage of households indicating ownership of a sanitary facility (%)
Arsenic- and salt-related health impacts	Arsenic consumption through drinking water (mg/L)
Coping and adaptive capacity	
Structural and physical options	
Engineered and built environment	Existence of structural measures such as dikes (binary)
Services (e.g., recovery relief, social networks, water management system, electricity, transportation, social capital index (−), medical services, access to market)	Percentage of households that received emergency recovery relief (%)
	Percentage of population using unsafe sources of drinking water (%)
	Percentage of population with no access to electricity (%)
	Percentage of population with accessibility of paved road (%)
	Percentage of population with access to primary health care center (%)
	Percentage of population with access to rural markets (%)
Social adaptation	
Educational adaptation options	
Past adaptation experience	Percentage of population that frequently adapts to salinity intrusion (%)
Awareness level	Percentage of households that attended disaster preparedness training/program before/after
Disaster (%)	
Education services	Percentage of population per education level (%)
Informational adaptation options	
Hazard mapping	Flood hazard mapping (ordinal)
Early warning	Percentage of households that received a warning message (%)
Behavioral adaptation options	
Psychological factors reflecting the adaptation intentions of farmers	Perceived self-efficacy and adaptation efficacy (ordinal)
Autonomous adaptation strategies and risky behavior	Percentage of farmers who reinforced or relocated their houses (%)
Alternative income-generating activities	Number of livelihood streams (n)

Table 2 continued

Social susceptibility	Indicator
Institutional adaptation	
Economic adaptation options	Percentage of farmers who bought insurance (%)
Laws and regulations	Percentage of boats that are equipped according to the license regulations (enforcement of safety codes)

Please refer to Table S4 for the full list of indicators as well as for the references. Note that indicators might point to positive or negative features of vulnerability and in some cases might also differ by hazards

the aftermath of (potential) hazards was assessed by a series of indicators by Mondal and Wasimi 2007 and Trinh et al. 2012. Aggregate indicators such as the density of public infrastructure and length of road systems were also common (e.g., Dang et al. 2011, Bhuiyan and Dutta 2011).

The housing sector was a major focus in the studies and many indicators were used to assess, e.g., the quality (Islam et al. 2014b), and the density of housing (Dang et al. 2011), or the relative extent of the uncontrolled planning zone (Balica et al. 2012). Swapan and Gavin (2011) investigated how the threats to livelihoods, culture, migration, and conflicts impact human security following salinity intrusion using a broad range of indicators including the number of land conflicts per year, the number of conflicts due to non-payment, and the share of migration driven by poverty.

Given the particularities of urban areas, the rapid pace of urban growth and increasing intra-inequalities (Szabo et al. 2015b; Szabo 2015), vulnerabilities related to urbanization processes need to be assessed separately. Accordingly, various authors used corresponding indicators such as urban population growth (Balica et al. 2012) or population density (Dang et al. 2011). Nevertheless, urban vulnerability was rather underrepresented in the studies. This might be a shortcoming given that many deltas, for example the Amazon (78.5 %, IBGE 2010), have a high rate of urbanization combined with poverty and low levels of infrastructure coverage, which have a potential to create high levels of vulnerability in these deltas—especially in the densely populated areas (see also Mansur et al. in this special issue). This might create future risk even in areas where current exposure to hazards is low, such as in the Amazon.

The reviewed papers provide a great variety of indicators related to coping and adaptive capacities within the deltaic areas. Related indicators were clustered into three different categories: structural and physical adaptation, social adaptation, and institutional adaptation (Noble et al. 2014). The structural and physical adaptation options are defined as options that "are discrete, with clear outputs and outcomes that are well defined in scope, space and time" (Noble et al. 2014) and include engineered and built environment options, technological options, and ecosystem-based options. None of the papers dealt with ecosystem-based options such as restoration of mangrove forests or maintenance of coral reefs for protection from coastal hazards. The vast majority of indicators were related to social options such as the provision of exposed populations with public services, including recovery relief, water supply services, electricity supply, waste treatment, transportation services, and medical services. More than half of these indicators were related to water supply, mainly addressing the share of the population without access to safe drinking water sources (e.g., Moglia et al. 2012; Few et al. 2013; Mallick et al. 2011), the wastewater investment options (Trinh et al. 2012), and the share of population with access to (useful) irrigation services (Dang et al. 2014). Concerning coping and adaptation, safe water supply is of crucial importance and was considered with respect to increasing temperatures and reduction of precipitation (e.g., Trinh et al. 2012), public health (e.g., Few et al. 2013), and in support of the recovery process after major hazards events (e.g., Mallick et al. 2011).

In addition, adaptive capacity is also fostered by options targeting vulnerability reduction of disadvantaged groups using educational, informational, and behavioral measures (Noble et al. 2014). Accordingly, a multitude of studies assessed indicators related to education, past experience, and the awareness level to capture the local coping and adaptive capacity. Most indicators related to the education category were categorical indicators related to the awareness and preparedness level (e.g., Balica et al. 2012) or relevant population proportions, e.g., the share of the population aware of the fact that water of low quality might cause diseases (Herbst et al. 2009). Only few studies used indicators related to the access to hazard and vulnerability maps.

A large number of papers focused on adaptation strategies or on the evaluation of psychological factors leading to behavioral changes. Within the adaptation context, livelihood diversification was most often investigated through indicators such as the number of livelihood streams (e.g., Islam et al. 2014b; Bosma et al. 2012) or the income that can be generated from non-fishery-based activities (Islam et al. 2014a). To assess agricultural adaptation, e.g., the percentage of farmers adapting to climate change by early planting or harvesting, investing in water storage or changing water use practices (Dang et al. 2014) were used.

Adaptive capacity is influenced by various institutional measures such as economic instruments, laws and regulations, and government policies and programs (Noble et al. 2014). Most indicators were related to economic instruments such as insurance arrangements (Dang et al. 2014) and access to formal bank credit (Islam et al. 2014a). Finally, capacity building and strengthening of institutions are of major importance for adaptation (Noble et al. 2014). This dimension has been captured by, e.g., the management capacity for the sectors' disaster risk reduction, readiness, responses, and recovery (Islam et al. 2013).

Discussion and outlook

This paper provides a systematic review of indicators used in vulnerability assessments in three globally relevant deltas–the Mekong, the Ganges–Brahmaputra–Meghna, and the Amazon. The proposed Deltas-SES vulnerability assessment framework guided the structured review of 55 papers. As an outcome, the framework was populated with 236 indicators that were assigned to vulnerability domains following Fig. 1. However, not all indicators are meant to be used in a single assessment which would likely lead to an inflationary number of (possibly highly correlated) indicators as criticized by, e.g., Meier (2009). Instead, these indicators serve as an "indicator library" constructed to provide an entry point for future delta assessments. However, knowledge of the specific delta context is needed before any of the indicators can be transferred to another delta-SES than the MKD, GBM, or Amazon. For example, the category "dependency on climate-sensitive production forms" is clearly influenced by the production forms and, thus, highly delta and even sub-delta specific.

A closer look at the indicator list (Table S4) shows that based on the review only, not all vulnerability domains could be populated appropriately (Fig. 2a). This is likely influenced by potential biases resulting from the review search terms, the prevalence of general papers using oversimplified indicators, or papers dealing with very specific and localized issues. However, there is also a more general, underlying pattern which can be observed in research, linking social and ecological research. While coupling both sub-systems is seen as a priority area of research to give more in-depth and dynamic insights into the functioning of (deltaic) systems (Dearing et al. 2015), in fact this review showed that social–ecological assessments are seldom implemented. Even in SES-type studies, indicators for social susceptibility and coping and adaptive capacities overwhelm those for the ecosystems (Fig. 2). Clearly, more effort is needed in the future to truly integrate ecological and social indicators in SES vulnerability assessments and, equally importantly, to consider the interactions of the two sub-systems through the consideration of indicators addressing (1) specific ecosystem services and (2) the impacts of human activities on ecosystems (these being already more prevalent), the two being linked through feedback loops. This is especially the case for ecosystem robustness, whereas ecosystem susceptibility was covered to a certain extent. Overcoming the prevailing emphasis of social over ecological components would definitely help to address sustainability concerns rooted in biophysical processes as much as their interaction with the social system (Epstein et al. 2013). A more thorough use of SES-based assessments would be definitely helpful. Brondizio et al. (2016) shows in this special issue how actionable information for policy makers can be framed using an SES-based conceptual delta model, e.g., to diagnose collective action problems in deltas.

Additionally, when assessments are carried out in the three deltas, they are mostly for single hazards only. When compared with earlier observations (Nicholls et al. 2008; Torresan et al. 2008), the review clearly showed that research has started focusing on multiple hazard types and assessment scales, clearly pointing to the diversity of threats these regions face. Nevertheless, hazards are still mainly tackled individually. Single-hazard assessments can lead to partial information and, in worst case scenarios, to maladaptation, as actions to reduce the vulnerability to one hazard could also lead to increased vulnerability to other hazards and thus to risk–risk trade-offs (Renn 2008). Examples of maladaptation in a multi-risk setting are flood protection embankments that isolate the coastal plain from its natural sediment source. For example, in the tidally influenced areas of the Ganges–Brahmaputra delta, embankments (polders) have prohibited sedimentation processes. This has caused 1–1.5 m land subsidence over the past 5 years, whereas adjacent natural mangrove forest areas have kept pace with sea-level rise (Auerbach et al. 2015).

Besides single-hazard assessments, the majority of studies have focused on specific small-scale case study areas within a delta. Deltas are heterogeneous in terms of biophysical as well as social, cultural, and political characteristics, and in terms of threats different regions in a delta face. Local assessments therefore provide specific information which is often not up-scalable or reproducible in different social or environmental settings. Delta-wide assessments do not allow us to capture the spatial heterogeneity in terms of social and environmental dimensions inherent to deltas' SES (Torresan et al. 2008; Birkmann et al. 2010). All these approaches provide useful information in terms of specific problems or general perspectives, but have limitations in terms of actionable information for local policy makers which would be best served by multi-hazard approaches accounting for the specific vulnerability profiles of sub-delta areas. There is a movement toward this direction manifested, e.g., in the Mekong Delta Plan which divides the delta into three regions with respective development trajectories proposed (Royal HaskoningDHV 2013).

The limitations of this review include the fact that the combination of certain search terms also produced results dealing with very specific and localized issues, including some papers which only referred to the three reviewed deltas but not focusing on them. Through this approach, some of the well-known publications dealing with delta vulnerability such as Syvitski et al. (2009) on the vulnerability of deltas to flooding ("sinking deltas") or Birkmann et al. (2010) on vulnerability profiles in the Mekong Delta could not be retrieved. Likewise, gray literature was not captured in the review, although some provide valuable approaches to deriving social–ecological indicators sets for vulnerability assessments in deltas (e.g., Bucx et al. 2010 and IMHEN 2010). Some of these papers and reports were, however, considered in our discussions. Additionally, the review scheme was also applied to these reports (e.g., Bucx et al. 2010; IMHEN 2010) to cross-check the outcome of the structured review. These publications were found to be a rich source of indicators, but the overall outcome was similar as achieved based on the 55 reviewed journal publications.

We paid special emphasis on three tropical/subtropical deltas, and therefore not all vulnerability aspects relevant for deltas globally might have been addressed. For example, polar deltas face different threats such as coastal erosion and melting of permafrost, leading, e.g., to the release of greenhouse gases such as methane and loss of established ice road and frozen coast connections (Ullmann et al. 2014). However, these deltas are typically only sparsely populated. This is to underline that there is a large variety of river deltas globally, and large differences in the social–ecological systems exist depending, e.g., on the size of the delta, climate zone, and population density. However, due to the great variety of different hazards the indicators we assessed responded to, we propose to use the hazards as entry point for the assessment and use of the respective indicators in a hazard-specific way. The range of hazards covered can be subsequently extended by considering further deltas with their specific hazard and risk patterns.

Despite these limitations, the structured review provides a broad overview of indicators used to assess the vulnerability of delta systems to various threats. The long list of indicators we identify clearly shows the disparity in the assessments' purposes and methodologies. However, the overlapping indicators or indicator categories also point to communalities which can serve as a basis to develop a library of indicators appropriate for comparisons of vulnerability across deltas, but also of vulnerabilities at the sub-delta scale. The present paper is designed as the first step in a research process. In a consecutive step, the indicator list will be assessed and extended based on stakeholder consultations in the three deltas following the proposed Delta-SES framework to finally propose a reduced and coherent list of indicators that can be used for vulnerability assessment at the sub-delta scale. This will allow capturing the nature of the indicators better (i.e., if they are process or impact oriented) and also to perform a causal analysis between hazards, impacts, and vulnerabilities for a better integration of local knowledge and ultimately for the sustainable development of deltas globally under changing environmental and societal conditions.

Acknowledgments The research is part of the international Belmont Forum project BF-DELTAS "Catalyzing action toward sustainability of deltaic systems with an integrated modeling framework for risk assessment" funded in part by the German Research Foundation (DFG) (Grant no.RE 3554/1-1) and NERC (Grant no. NE/L008726/1). Zita Sebesvari and Fabrice Renaud would like to acknowledge the funding provided by DFG. We are grateful to the two anonymous reviewers for their constructive feedback.

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