Vulnerability assessments of coastal river deltas - categorization and review

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Abstract Coastal river deltas are densely populated areas and hotspots of vulnerability. The delta's ecological, social, and economic components are vulnerable to a wide variety of natural and anthropogenic threats. Sea level rise, climate variability, and rapid socio-economic development exert pressure on the already highly dynamic regions. To protect river deltas and their components, it is necessary to assess the degree of vulnerability so that mitigation efforts can be recommended to stakeholders and policy makers. Many such vulnerability assessments have been undertaken for river deltas. However, as vulnerability and related terms, such as resilience, coping-, and adaptive capacity only entered geosciences in the past decades, these terms are often used ambiguously. This makes it hard to compare existing studies, which not only interpret the related terms differently, but also consider completely different threats to deltas and their components, at different spatial and temporal scales. A comprehensive overview of studies addressing vulnerability of river deltas is missing. This paper presents a review, based on a consolidated set of definitions of vulnerability and related concepts in the context of coastal river deltas. All studies reviewed were categorized depending on their focus on either the ecologic, social, or economic component of river deltas, and were classified according to their spatial scale, temporal resolution, and numerous other research characteristics. Clear trends on dominant research foci in the field of river delta vulnerability could be extracted. Additionally, based on the findings presented here,

recommendations for future assessments considering existing research gaps, are formulated.

Introduction

Coastal river deltas are low-lying plains that form where rivers meet the ocean. Over long geologic time spans, organic matter transported by most rivers accumulated at the river mouth and led to reserves of oil and gas in many delta areas globally. Often times, alluvial soils characterize the delta plains. In an undisturbed state, deltas are home to fragile ecosystems, such as salt marshes, wetlands, and coastal forests (Wang et al. 2011b). The rich biodiversity, land fertility, and abundance of natural resources has attracted humans to coastal river deltas for centuries (Anthony 2014; Kuenzer and Renaud 2012; Overeem and Syvitski 2009). Over time, humans gradually transformed coastal river deltas to suit their needs through socio-economic development, including the expansion of agriculture, as well as urbanization and industrialization. Therefore, today, coastal river deltas are among the most densely populated areas on earth (Bollmann et al. 2011; Burkett et al. 2001; Higgins et al. 2013; Kuenzer et al. 2013b; Woodroffe 2002). According to Overeem and Syvitski (2009), river deltas such as the Nile, Ganges Brahmaputra, Yangtze, and Pearl River deltas have a population density of over 1000 people/km^2, compared to the global average of 45 people/km^2. The impact of human activities can be felt in the disturbance of natural resources, such as the logging of coastal forest, the drainage of wetlands, and the redirection of the river water to name only few examples. Additionally, water-, soil-, and air pollution, as well as ground compaction due to

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underground oil, gas, or groundwater extraction are noted in many deltas globally (Anthony 2014; IPCC 2014a; Kuenzer et al. 2014a, 2014b; Pillsbury 1981; Syvitski 2008; Syvitski et al. 2005, 2009). The human induced sinking of many deltas is aggravated by sea level rise, prevalent at all coasts of the earth. Overeem and Syvitski (2009) estimate that 33 major river deltas collectively share an area of 26,000 km^2 below local sea level, while another collective area of 70,000 km^2 is below 2 m of local sea level and thus vulnerable to sea level rise (SLR). This figure might increase by 50 % using 21st century SLR projections (Syvitski et al. 2009). Additionally, upstream developments impact deltas (IPCC 2007; Ottinger et al. 2013). Dam construction, related sediment retention, upstream water consumption and diversion for social and economic use, all lead to changes in river flow and sediment supply downstream, which in turn affects river deltas ecologic, social, and economic activities by aggravating processes such as land degradation, erosion, and salt water intrusion (Kuenzer et al. 2013a; Saito et al. 2007; Woodroffe 2002).

Due to all these challenges, coastal river deltas have been recognized as hotspots for vulnerability by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007). By assessing the degree of vulnerability of the river delta system and its social, economic, and ecologic components, it is possible to determine to what extent these systems are able to cope with and adapt to the impacts they are subjected to. Various organizations, such as the World Wildlife Fund (WWF 2014), the United Nations Office of Outer Space Affairs (UN-SPIDER 2014), and the United States Geological Survey (USGS) are engaged in vulnerability and resilience assessments of river deltas. Of course these are just three examples – there are hundreds of global, national, regional, and local decision makers and stakeholders, research institutions, companies, and individual experts who assess river delta vulnerability. Generally, these organizations or individuals focus on their specific interest (e.g., WWF on biodiversity related issues, UN-Spider on natural disaster related aspects, the USGS on coastal geology, and geohazards), while other aspects are given a lesser priority or are not considered.

However, coastal river deltas are complex systems where each of the ecologic, social, and economic components are highly interrelated. Furthermore, the degree of vulnerability is determined not only by internal processes and threats from within the delta, but also by external processes originating from the ocean, upstream areas, the subterranean, as well as from overall climate. As recommended by Kuenzer and Renaud (2012) and Renaud et al. (2013), it is time to use a multidisciplinary approach to assess the state of deltas with experts of various disciplines, including stakeholders from various levels of governance.

Assessing the degree of vulnerability or resilience of a coastal river delta is not only difficult due to the complexity of the river delta system, but also due to the fuzziness of the terms involved. Results are often ambiguous, as it is not possible to measure vulnerability or resilience objectively (Birkmann 2006). The quality of vulnerability assessment depends on the foci of the assessors, stakeholders, and beneficiary involved. Results of vulnerability assessments may for example conflict with the interests of other actors that have a stake in the area where the assessment is conducted. Here, the fuzziness of the definition of vulnerability creates an opportunity to influence the outcome of vulnerability assessment in favor of e.g., a specific component, or management policy just like for many environmental impact assessments (EIA). Therefore, a lot of responsibility is with the scientific community, to assess the complex topic river delta vulnerability in a stringent, multi-facetted, and transparent way.

The main goal of this paper is to provide a comprehensive review of studies assessing vulnerability of coastal river deltas, categorizing, comparing, and discussing the individual studies, the methods employed, and the trends observed. This is based on a brief discussion of the definition of vulnerability, and a detailed scheme to classify river delta vulnerability assessments with respect to their general application characteristics, and the methodology used to derive vulnerability. Furthermore, research gaps are identified and future recommendations are presented.

Vulnerability: definition of terms and concepts

The term 'vulnerability' has its origins in the study of threats of natural hazards on socio-economic systems (Birkmann 2006; O'Keefe et al. 1976). Vulnerability is a broad term, that researchers and experts discussed, reformulated, and expanded upon for various applications in different disciplines, such as economics, social sciences, biology, medicine, psychology, computer science, and numerous others (Adger 2006; Birkmann 2006; Cutter 2006; De Lange et al. 2010; Füssel and Klein 2006; Janssen and Ostrom 2006). Table 1 lists some examples of attuned definitions of vulnerability, as used by several institutions involved in vulnerability studies. But, due to the broad use and intangible, complex, and ambiguous nature of the term 'vulnerability', researchers such as Timmerman (1981) as cited through Füssel and Klein (2006) stated that: '*vulnerability is a term of such broad use as to be almost useless for careful description at the present, except as a rhetorical indicator of areas of greatest concern*'. It is therefore argued that, rather than attuning the term 'vulnerability' to suit specific needs, this review will use the term in an as 'neutral' as possible fashion (i.e., not attuned to a specific discipline) for this paper, as defined by Turner et al. (2003) (see Table 2).

Vulnerability is not an independent concept. Researchers, such as Liverman (1990) after Füssel and Klein (2006), and Gallopín (2006), and Smit and Wandel (2006) have argued

Table 1 Examples of attuned definitions of the term 'vulnerability'

Institution	Definition of vulnerability	Source
IPCC (International Panel of Climate Change)	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity.	IPCC (2007)
UN/ISDR (United Nations International Strategy for Disaster Reduction)	The conditions determine by physical, social, economic and environmental factors or processes, which increase susceptibility of a community to the impact of hazards.	Birkmann (2006)
UNDP (United Nations Development Programme)	A human condition or process resulting from physical, social, economic, and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard.	Birkmann (2006)

Table 2 Definitions of vulnerability, resilience, coping capacity, and adaptive capacity as used for this review

Concept	Definition
Vulnerability	The degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or a stress/stressor (after Turner et al. (2003)).
Resilience	The degree to which a system and its components are able to anticipate, absorb, accommodate, or recover from perturbations or stress/stressor.
Coping capacity	The ability of system components and pre-existing mitigation efforts that protect systems from negative impacts.
Adaptive capacity	The ability of a system to increase the coping capacity of individual system components.

that vulnerability has a strong relationship with other terms, although which terms are related is also dependent on the various disciplines of the researchers and their interpretation of each concept. Since the main focus of this paper is on vulnerability, the discussion is limited to the closely related concepts of resilience, coping capacity, and adaptive capacity.

Resilience is defined by the IPCC as: '*The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.*' (IPCC 2014a). Resilience, like vulnerability, relates to the overall system state and ability (or inability) to function, and is independent from the individual stability of its components (Adger 2000). This study adopts these definitions for this review as the counterpart of vulnerability in terms of the status of the coastal river delta system.

Coping capacity and adaptive capacity have overlapping definitions and have various interpretations for different disciplines. Coping capacity is defined by Smit and Wandel (2006) as: '*the conditions that a system can deal with, accommodate, adapt to and recover from*'. The IPCC

(2014b) differentiates between coping and adaptive capacity through different timespans; coping capacity is the ability of systems to overcome adverse conditions in the short to medium term, while adaptive capacity is the ability of systems to adjust to potential damage, take advantage of opportunities, or to respond to consequences (IPCC 2014b). This review interprets coping capacity for this paper as the ability of system components and pre-existing mitigation efforts that protect systems from negative impacts. Thus, a high coping capacity can make a system (−component) more resilient to hazards and threats, while a lack of coping capacity makes the system more vulnerable, in the event the system is affected by a negative impact. This review interprets adaptive capacity as the available resources (such as money or institutional knowledge) available to the system (−component), to implement mitigation efforts or regenerate new or existing mitigation efforts to protect components of the coastal river delta from negative impacts. In other words, adaptive capacity determines the ability of a coastal river delta system to increase the coping capacity of individual components. However, a high adaptive capacity is meaningless if stakeholders choose not to implement or establish mitigation efforts to increase coping capacity, or implement maladaptive actions which increase vulnerability of the system (IPCC 2014b).

Vulnerability of river deltas

Figure 1 depicts in a simplified manner how the concepts of vulnerability, resilience, coping and adaptive capacity can be applied for a coastal river delta. The socio-ecological system
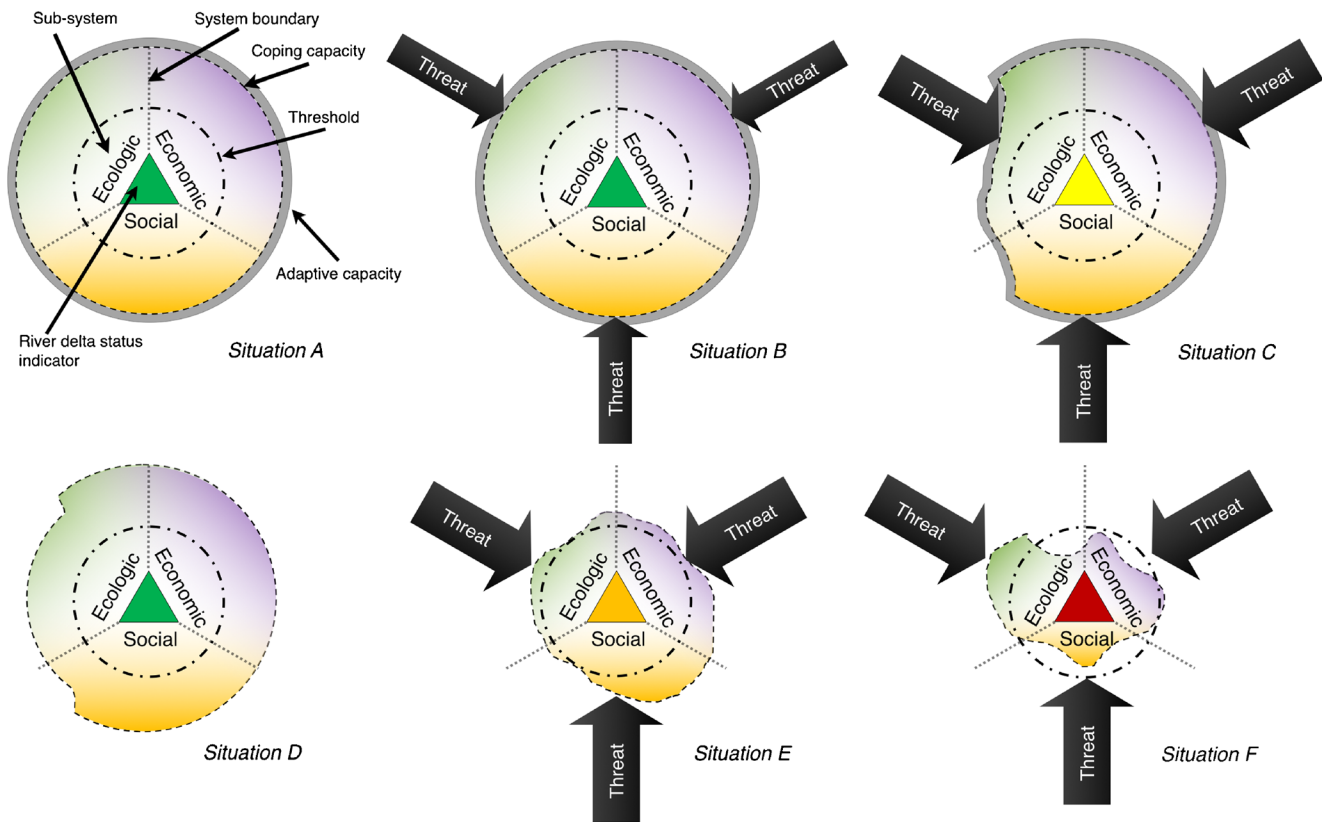
Fig. 1 A graphical representation how vulnerability and related terms influence the state of a river delta and its ecologic, social, and economic social components

that is the coastal river delta is shown as a triangle, where the color of the triangle signifies the overall status of the coastal river delta system (healthy/undisturbed/unthreatened=green, disturbed/threatened=yellow, majorly disturbed/severely threatened=red). Coastal river deltas are systems which can be subdivided into three components, namely:

1. The social component (orange section in Fig. 1), covering aspects such as e.g., demographics, inhabitant's health, employment rate, education rate etc.
2. The economic component (purple section in Fig. 1), covering aspects such as e.g., industrial activity, transportation, tourism activity etc.
3. The ecologic component (the green section in Fig. 1), covering aspects such as e.g., biodiversity, flora and fauna of ecosystems etc.

Each of these components has a certain boundary, which is illustrated in Fig. 1 as a dotted line that originates from each corner of the triangle. Note, however, that the components are strongly interrelated and overlap (e.g., socio-ecology, socio-economics), as certain objects, processes, or policies cannot be clearly assigned to only one specific component. Yet if all objects, processes, or policies are classified as being part of the 'coastal river delta' system without further categorization, the results of vulnerability assessments would be even more unclear.

The coastal river delta in situation A is stable and resilient: an 'ideal' situation. Each of the system components has a high coping capacity, which enables it to deal with different threats. Note that for simplification, the coping capacity is represented as a single line, but in reality, there are various coping capacities for various negative impacts. The components also have a certain adaptive capacity, illustrated as a gray circle around the coping capacity. This symbolizes the means available to further bolster the coping capacity where necessary, or to quickly recover in case the coping capacity is diminished. Like coping capacity, the illustration of adaptive capacity is simplified as in reality adaptive capacity is distinguished between different resources available.

Situation B shows that the coastal river delta is being threatened by external processes (thick black arrows). The repercussions of these impacts are minor, as the river delta has a high coping capacity (e.g., strong enough levees can cope with a minor storm surge, protecting the system components that are located inland). Deltas in developed countries (e.g., the Rhine-Meuse-Scheldt Delta, with advanced storm barriers (Wesselink 2007)) could fall under this category.

In Situation C, the impacts threatening the delta intensify and gradually erode the coping capacity. The coastal river delta becomes less resilient and more vulnerable to these impacts, as is indicated through the yellow color of the triangle. The degree of coping capacity is still above a certain threshold (the dash-dotted circle), and thus there are no real reasons for concern. Each system component responds differently to impacts, and some may lose their coping capacity faster than others. Due to the strong interrelationships of each component, if one component becomes more vulnerable and loses coping capacity, other components may be affected as well. For example, if a pollution event is threatening the habitats of certain fish species (ecologic component), it also threatens the fishing activities (economic component) and the livelihood, of the local population (social component) in the delta, even though these components were not directly affected by the event.

Situation D visualizes a recovering coastal river delta system, after being affected by threats visualized in situation C. Stakeholders in the river delta use their available resources (adaptive capacity) to restore the lost coping capacity, in preparation of future threats. By doing so, the degree of adaptive capacity is diminished, but the state of the river delta system is bolstered. The state of the river delta changes from somewhat vulnerable to somewhat resilient.

Situation E, the river delta is under major threat from impacts, which erode the coping capacity of all system components drastically. The river delta is now vulnerable, as the coping capacity of certain components has eroded to almost below the threshold line. There is no longer enough adaptive capacity to bolster these components. An example of this situation could be the state of the levees in the Mississippi River Delta during the Hurricane Katrina event.

Situation F shows a very vulnerable river delta, indicated by the red triangle. The coping capacity has eroded below the threshold, which could lead to a regime shift or collapse of certain systems within the components, a complete component, or the whole delta (e.g., a tsunami, which erases all human life and infrastructure in a delta can lead to a complete loss of the social and economic component of a delta).

Processes affecting coastal river deltas

Processes that affect coastal river deltas can be categorized as:

- Internal processes: processes that originate from within the delta that affect the delta system and its components.
- External processes: processes that originate from areas outside the delta that affect the delta and its components.

Based on origin, this review further differentiates:

- Natural processes, such as precipitation, storms, the tide etc.
- Anthropogenic processes, such as urbanization, industrialization, and related effected such as pollution, water consumption, levee construction etc.

Based on the type of impact, this review further differentiates:

- Beneficiary impacts: benefiting certain components, reducing their degree of vulnerability by bolstering coping or adaptive capacity
- Adverse impacts: making certain components more vulnerable by reducing their coping or adaptive capacity.

Processes not only affect the coastal river deltas and its components, but also exacerbate or weaken one another in various degrees (e.g., a storm surge combined with RSLR (relative sea level rise, which is absolute sea level rise combined with regional ground subsidence (IPCC 2007, 2014a; Sánchez-Arcilla et al. 2008)). A simplified graphical representation of a typical delta can be found in Fig. 2. Note that the presented list of internal and external processes is by no means exhaustive; there may be many more internal or external processes of different magnitudes in a spatial or temporal sense. Furthermore, the processes cannot be classified in a binary 'adverse' or 'beneficial' effect. Each system component (and the aspects in the delta attributed to each component), reacts differently to each process and is directly or indirectly affected. As such, linkages between system components (ecologic, social, and economic), their properties, and the processes affecting them should be investigated thoroughly for each delta before the degree of vulnerability can be assessed.

External processes

External processes are processes which affect the delta but originate outside of it (such as from upstream areas or the ocean). The river delta is furthermore affected by other climatological and earth system processes. Rivers supply its basin and delta with fresh water and sediment from upstream areas. A constant influx of these resources is very important for the delta. Excessive consumption of fresh water, and inhibited sediment flow in upstream areas due to socio-economic activities and management policies (e.g., dams, water quotas), leads to decreased availability of these resources in downstream areas, which leads to water shortage (for human consumption, industrial, and agricultural use), salinization, erosion, and compaction in these regions (Joyce 1997; Ottinger et al. 2013; Pillsbury 1981; Saito et al. 2007; Woodroffe 2002; Woodroffe and Murray-Wallace 2012). Construction in and around the river (e.g., hydropower dams, river rerouting) further change river flow rates, and induce abnormal flood or

Fig. 2 Simplified representation of a typical coastal river delta. **a)** The river surrounded by dykes **b)** Urban pollution source **c)** Industrial pollution source **d)** Water diversion for agriculture **e)** Water diversion for aquaculture **f/g)** Wetlands in the delta **h)** Deforestation for agriculture **i)** Reforestation efforts **j/k)** Natural resource extraction **l)** Salt water intrusion **m)** Sand mining **n)** Fishing activities, and algal blooms **o)** Water logged areas due to dyke development **p)** Harbor development and land reclamation (figure modified based on (Kuenzer et al. 2014b))

drought events. Abnormalities in river flow increase the degree of vulnerability of riverine, terrestrial and subaqueous deltaic habitats that regular fresh water and sediment influx, and periodic flooding (Carriquiry and Sánchez 1999; Dudgeon 2000; Joyce 1997; Kuenzer et al. 2013a; Vörösmarty et al. 2010).

Socio-economic activities in upstream areas also lead to the degradation of river water and sediment quality through human, industrial, and agricultural waste (e.g., trash, heavy metals, fertilizers and pesticides) (Wong et al. 2002). Deltas are especially vulnerable, as these pollutants disposed along the river accumulate in the delta. Heavily polluted water in the delta limits its use for industrial and agricultural activities, pose a risk to the local population when consumed directly or indirectly (Barbier et al. 2011; Howard and Olulu 2012; Joyce 1997; Wong et al. 2002), while decreasing the vigor of ecosystems (e.g., leading to algal blooms, and decreasing biodiversity) in both the terrestrial and subaqueous delta (Jennerjahn and Mitchell 2013; Kuenzer et al. 2013a).

Storm surges, tsunamis, and pluvial floods threaten the low lying coastal river deltas by means of floods and coastal erosion. These hazards are exacerbated by RSLR, ocean currents, tidal movements, climate variability, and management practices in the upstream areas. Construction efforts in the delta such as dyke and storm sluices (Fig. 2a) can help mitigate these effects, protecting the low lying areas and the system components and activities therein (Barbier et al. 2011).

Processes and activities in the ocean also influence the coastal river delta, e.g., decreased fishing staples for human livelihoods due to ocean warming, ocean acidification, algal blooms, sediment mining and unmanaged fishing practices.

Meanwhile, offshore oil extraction can lead to oil spill incidents (Fig. 2k), which have a strong negative effect on the biodiversity in the river delta (Kuenzer et al. 2014a, 2014b; Mendelssohn et al. 2012; Neff et al. 1987).

Internal processes

Internal processes are processes, which originate from inside of the delta itself and impact it. Water management practices as well as land use practices are some examples.

As surface water supplies in river deltas are often slightly saline or too polluted, this is often compensated by extracting ground water (Fig. 2j). Improper management of groundwater extraction leads to a receding ground water table and land compaction, while allowing ocean water to penetrate further inland; a process leading to salinization (Fig. 2l) (Anthony 2014; Changming et al. 2001; Ferguson and Gleeson 2012; Syvitski 2008; Vandenbohede et al. 2008; Woodroffe and Murray-Wallace 2012). Compaction can also be caused/exacerbated through the construction of heavy objects (Kuenzer and Renaud 2012), while salinization can also be caused/exacerbated by excessive irrigation practices (Pillsbury 1981) (Fig. 2d). If the water shortage is severe, governments in the coastal river deltas may be forced to reallocate the water supply, focusing on socio-economic activities (Fig. 2b, c), while rationing water meant for natural areas, such as wetlands, (Fig. 2d, e, f, g) decreasing their vigor and biodiversity (Wang et al. 2011b). In other parts of the delta, reforestation efforts might be conducted to compensate for habitat loss elsewhere (Fig. 2i).

Urban and industrial developments in the river delta create jobs and improve the livelihood of the population. This may have positive effects (e.g., increasing the average income of a certain demographic group) and negative effects (e.g., pollution). Land use intensification, due to socio-economic development increase the pressure on natural resources while exacerbating pollution. Improperly managed land use planning leads to fragmentation or complete removal of natural areas (Fig. 2e, h, p), whose ecosystem services play a vital role in the river delta, such as water and carbon storage, water purification, and protecting hinterland areas from natural disasters such as flooding (Bi et al. 2011; Jennerjahn and Ittekkot 2004; Jennerjahn and Mitchell 2013; Li et al. 2010).

Oil and gas reserves are commonplace in delta areas. The extraction of non-renewable natural resources provides an economic boost (Fig. 2k, m), but exacerbates ground-, water-, and air pollution as well as subsidence rates. Natural resource extraction may lead to localized earthquakes in certain situations (Syvitski 2008; Syvitski et al. 2009; Van Eck et al. 2006), while also posing a threat to system components in case of a pollution incident (Ko and Day 2004; Kuenzer et al. 2014b).

Review methodology

A total of 54 vulnerability assessments which pertain to coastal river deltas or related (e.g., estuary) areas were analyzed. Some studies assess the vulnerability of coastal zones in general, but include the assessment of deltas in their study. This is because coastal river deltas are a sub-category of coastal zones, and methods that assess vulnerability in coastal zones could (and have been) spatially transferred and expanded upon to accommodate the complexity and intricacies of coastal river deltas. Our analyses also includes coastal zone assessments wherein a coastal river delta plays a central role.

There is no single standardized unit available for quantifying vulnerability or resilience. As Birkmann (2006) puts it: "*we are still dealing with a paradox; we aim to measure vulnerability, yet we cannot define it precisely*". Therefore, the choices made by the assessors considering the spatial and temporal scale of the study, the focus delta components and threat, data availability and selection, as well as the method used to combine vulnerability parameters have a major influence on the outcome and quality of the vulnerability assessment. Due to this complexity, a list of 9 criteria has been devised with which this review will classify or categorize the vulnerability assessments, in order to work out obvious commonalities and differences of the studies investigated, to highlight trends, and to reveal research gaps. These criteria have been categorized in two groups, namely: general (topic related) vulnerability assessment characteristics (4 criteria), and methodical vulnerability assessments characteristics (5 criteria).

Based on the general vulnerability assessment characteristics (presented in detail and with their sub-categories and explanations in Table 3) it is the goal to answer questions such as:

- Which delta system component and which aspects are considered in the vulnerability assessment (multiple answers possible to accommodate multifocal assessments)?
- Which types of processes are considered in the vulnerability assessment?
- What is the spatial scale of the vulnerability assessment?
- What is the temporal scale of the vulnerability assessment?

With the methodical vulnerability assessment characteristics (presented in detail and with their sub-categories and explanations in Table 4) it is the goal to answer questions such as:

- Which types of data are considered in the vulnerability assessment (multiple answers possible to accommodate highly dynamic studies)?
- How were the vulnerability parameters that were used to derive the degree of vulnerability selected?
- How are these parameters rated (i.e., converted into a unit independent parameter)?
- How are these parameters weighted (i.e., to increase or decrease the importance of parameters in a vulnerability index)?
- How is the vulnerability assessment result validated?

Each paper that is reviewed is categorized (in the case of Aspects considered and Data considered) or classified as a specific sub-category. The results of which are presented in Fig. 3.

Review of vulnerability assessments

This section consists of two sub-sections, one for general and methodical characteristic presented in the previous section. These two sections have sub-sections of their own, for each characteristic discussed in the previous section. All studies were reviewed and are shortly presented, but for each criteria, the most representative vulnerability assessment is presented in detail.

General characteristics of river delta vulnerability studies

The review results of all general characteristics can be found in Fig. 3. These results are discussed for each individual characteristic in the following sub-sections.

Table 3   General characteristics and their sub-categories, with explanations, as used for the review of vulnerability assessments

Category	Sub-Category	Explanation
Delta Components Considered *(Categorized results)*	Ecological Component	Aspects such as flora or fauna species, location and vigor of wetlands, mangroves, geophysical properties…
	Social Component	Aspects such as demographics, health, livelihood, location of settlements, population…
	Economical Component	Aspects such as agriculture crop type, aquaculture, natural resource extraction, GDP, industry type, mitigation efforts…
Processes Considered *(Classified Result)*	Natural	Natural processes, such as erosion, subsidence, typhoons, earthquakes, weather are considered
	Anthropogenic	Anthropogenic processes, such as pollution, industrialization, water usage are considered
Spatial Scales *(Classified Result)*	Local	Assessments conducted on a local scale (e.g. district, municipal)
	Regional	Assessments conducted of a delta and its direct environment
	Comparative	Assessments conducted of multiple deltas on earth that are non-adjacent to one another
Temporal Scale *(Classified Result)*	Uni-temporal	Assessments that focus on 'current' vulnerability
	Multi-temporal/Time series	Assessments that study the differences in vulnerability degree over time

Delta components considered

When categorizing delta vulnerability assessments in regards to which delta components the studies considered (ecologic, social, economic), the review reveals that the majority of coastal river delta vulnerability assessments consider ecologic (90 %), after which come the economic (56 %), and social (56 %) components. See also Fig. 3a. Sums of over 100 % are possible, because several studies focus on – for example – two component (ecological, social, and economic) with equal weight. In this case, the study was assigned to multiple components.

While analyzing patterns in delta components considered, it became apparent that three major trends of vulnerability assessment types can be identified, namely:

- Highly focused vulnerability assessments, which primarily pertain to a specific component,
- Semi-focused assessments, which incorporate various components but do not focus on any specific component,
- Multi-component vulnerability assessments, which are studies that focus on all components in a very detailed fashion.

The majority of studies in this review are semi-focused studies that combine a small number of parameters from several or all of the various ecologic, social, and economic components of each delta depending on the data available or interests of the assessors. While very strictly focused studies

may distract from the bigger picture of the river delta system vulnerability status, semi-focused studies tend to generalize due to the fewer number of parameters of each considered delta component.

That the ecologic component are widely considered in river delta vulnerability assessments is not surprising, as geophysical properties (a part of the ecologic component) of deltas are naturally a large determinant of the vulnerability in these areas. Studies such as Sánchez-Arcilla et al. (2008) and Rao et al. (2009), Elewa et al. (2012), Rasul et al. (2012), Marriner et al. (2013), Fatorić and Chelleri (2012), Frihy (2003), Frihy et al. (2010), Frihy and El-Sayed (2013), Tri et al. (2013), Boori et al. (2010) and Shi et al. (2000) are highly focused on geophysical aspects of the ecologic component. These studies combine data from sources such as measurement stations (such as tidal gauges), transects, and sometimes EO data, to derive information on accretion and erosion, wave height, tide range, land surface elevations, soil type, and sea level rise, which then are used to derive vulnerability (e.g., to storm surges, SLR etc.). As such, these are highly focused geophysical studies. Only few assessments (such as Shi et al. (2000)) that are heavily focused on geophysical parameters consider other aspects – but to a far lesser extent – as well. The other aspects considered are predominantly the social and economic components, in the form of (sub-)national GDP and population density figures, mostly extracted from census data or open geospatial data.

Examples of highly focused and semi-focused social component vulnerability assessments are Rygel et al. (2006)

Table 4 Methodical characteristics and their sub-categories, with explanations, as used for the review of vulnerability assessments

Category	Sub-Category	Explanation
Data Considered *(Categorized Results)*	Interviews/Questionnaires	Surveys among the local population or stakeholders
	In-situ field measurements	Walking transects, field mappings (excludes questionnaires)
	Measurement stations	Readings from static measurement stations (tidal stations, pollution monitoring)
	Census data	Data as supplied by census bureaus
	Earth Observation (EO) data	Airborne or satellite data such as multispectral, hyperspectral, radar, or LiDAR data
	Third party products	Data as supplied by other institutions or authors
Parameter Selection Method *(Classified Result)*	No selection	Once parameters are chosen, all of them have been used, regardless of correlation
	Statistic method	Parameters are selected through a statistical analysis, such as Principal Component Analysis (PCA), to exclude highly correlated parameters
	Assessor or expert determination	The assessors have decided themselves or through advice of external experts or stakeholders which parameters to exclude
Parameter Unit Independent Rating Method *(Classified Result)*	Expert determination	Unit independent ratings have been devised by external experts or stakeholders
	Assessor determination	Unit independent ratings are devised by the assessors themselves
	Previous studies	Unit independent ratings are re-used from previous studies
	Not applicable	Methodology does not require unit independent ratings (e.g. discussions)
Parameter Weights *(Classified Result)*	Expert determination	Parameters are weighted or ranked by importance by external experts or stakeholders
	Assessor determination	Parameters are weighted or ranked by importance by the assessors
	Automatic determination	Parameter weights are automatically ranked (e.g. with artificial neural networks)
	No weights	No parameter weights are used
	Not applicable	Using parameter weights was not applicable for the assessment
Validation of results *(Classified Result)*	Validated	The results of the assessments are validated
	No validation conducted	The results of the assessments are presented 'as is' and are not validated

(highly focused), Kleinosky et al. (2006) (semi-focused), Ge et al. (2013) (semi-focused), Cutter et al. (2000) (semi-focused), and Burton and Cutter (2008) (semi-focused, discussed below). The most notable trend of these assessments is that these assessments are heavily reliant on census data, and as such, the study areas of these assessments are generally located in areas where a large abundance of census data is available (i.e., developed countries, most notably the U.S. and China). These studies incorporate a large amount of socio-economic parameters (20 or more), which are reduced to a more manageable number to avoid over-representation of particular phenomena, which is highlighted in the "Parameter Selection Method" section. There are also semi-focused

vulnerability assessments that focus on socio-economic aspects but do not excessively use census data. Van der Veen and Logtmeijer (2005), who studied hotspot analysis of economic areas in the Rhine-Meuse delta, Khang et al. (2008), who assessed salinity intrusion and its effect on crop areas for the Mekong Delta, and Thatcher et al. (2013) are representative examples. The latter uses and built upon the CVI (Coastal Vulnerability Index) method to estimate the vulnerability of the Mississippi Delta and surrounding areas to SLR. The CVI method from Gornitz (1991), Gornitz et al. (1994), and Thieler and Hammar-Klose (1999) is a popular method to assess vulnerability in coastal areas, and some assessors have used it to assess vulnerability in coastal river delta

Fig. 3 Classification and categorization results of the coastal river delta vulnerability assessments for each of the general characteristics
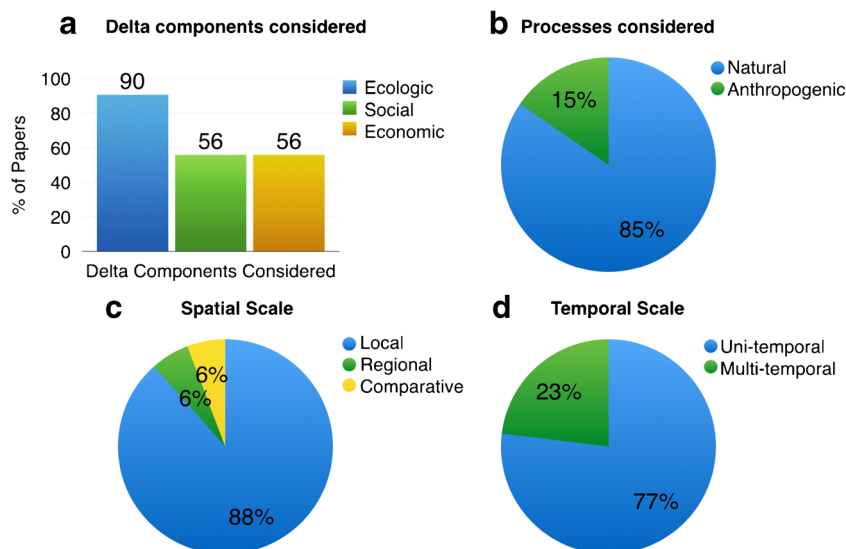
areas as well. Since the CVI method originally only includes geophysical parameters, Gornitz et al. (1994) underscored the addition of social, and economic component related characteristics in future assessments for better results. This has been addressed by Thatcher et al. (2013) (amongst many others) by including a range of economic parameters pertaining to commercial and residential building values, public works locations, as well as social parameters such as urban pixel density and population density, using datasets such as census data, U.S. Federal Emergency Management Agency (FEMA) and National Oceanic and Atmospheric Administration (NOAA) datasets, respectively, combining them with geophysical parameters from the CVI from a previous coastal vulnerability assessment by Pendleton et al. (2010). Thatcher et al. (2013) proceeded to compare CVI and devised CEVI (Coastal Economic Vulnerability Index), concluding that the CEVI can provide more information about the socio-economic vulnerability than the CVI (Thatcher et al. 2013). The choice made by authors of assessments to use many or few parameters from census data is further highlighted in the "Data Considered" section.

While we previously elucidated studies that focus specifically on the geophysical aspects within the ecologic component, other aspects of the ecologic component (i.e., not only geophysical aspects, but also flora and fauna related aspects) are incorporated in only a third of the assessments reviewed. For example, the study of Omo-Irabor et al. (2011) focused on the threats posed to mangrove forests in the Western Niger Delta. Mangrove forest areas were classified using Landsat data using a Maximum Likelihood classification. By using data from 1987 to 2002, they estimated the total amount of mangrove forest loss. Socio-economic parameters, such as population pressure, deforestation, poverty and civil conflicts, as well as environmental parameters such as carbon dioxide

content, relative humidity, temperature, presence of alien invasive species, sea-level rise, precipitation and pollutant input, were incorporated in the study. A literature review was used to estimate the unit independent ranking of each parameter, while parameter weights were determined using interviews of experts. By using a Spatial Multi-Criteria Analysis (SMCA), the weights were normalized. The vulnerability was estimated through a weighted linear combination. The final result is a continuous map showing the mangrove vulnerability (Omo-Irabor et al. 2011). Other assessments that have a similar focus on environmental aspects are Jiang et al. (2005), and Jiang et al. (2011), assessments of wetland vigor in the Liaohe River Delta and ecosystem risk in the Yellow River Delta, respectively.

Besides semi-focused vulnerability assessments that consider socio-economic aspects, there are also highly focused economic vulnerability assessments such as Liersch et al. (2013), who focuses on rice crop production due to water shortage, and Hang et al. (2009), who focuses on the vulnerability of local population as a result of consumption of contaminated rice crops due to industrial PTE (potentially toxic elements). The assessment by Hang et al. (2009) analyzes 155 soil and rice samples, selected based on their landform and proximity to industrial activity. The estimated daily intake, target hazard quotient (the ratio of consumption of potentially toxic elements (PTE's) with and without ill effects) and a population hazard index were computed. The spatial distribution of PTE's in the soil of the study area showed that the hotspots of pollution are in close proximity of the corresponding industrial activity (e.g., soil polluted with mercury and arsenic pollution follow the same geographic trend as industrial areas that use pesticides). In some areas, the estimated PTE intake of specific elements due to consumption of contaminated rice was higher than the reference oral dosage (such

as copper (3.9 %) and lead (1.9 %) among adults). Children consuming polluted rice from these areas are especially vulnerable (Hang et al. 2009). A similar chemical study, conducted by Lin et al. (1997), focused on reduced water well quality in the Arkansas Delta due to agricultural chemicals.

Only a minority of assessments consider anthropogenic mitigation aspects, which are part of the economic component in deltas. The majority of the studies that incorporate anthropogenic mitigation aspects are highly focused assessments. This does not necessarily mean that in reality anthropogenic mitigation aspects are hardly considered, as many studies can also be conducted by engineering or consultancy bureaus, specifically catered to finding weaknesses in existing coastal defenses. These reports may not always be open for public viewing. Several studies are specifically oriented at assessing the degree of vulnerability of mitigation efforts, such as Torres et al. (2000). In this study, the vulnerability 1200 miles of levees in the San Joaquin Delta (California, U.S.) to liquefaction induced by earthquakes is estimated. The delta is in proximity of several fault lines, although it is uncertain whether or not the fault line under the delta region is active. Thus, Torres et al. (2000) made two assessments of peak ground acceleration: an assessment considering an active fault system under the delta, and another considering smaller faults west of the delta region. The outcomes of the models suggest that it is unlikely that the entire delta would be affected by a major earthquake originating within or outside the delta area, and that it is more likely that localized earthquakes are the biggest threat to levees. In order to assess levee fragility to earthquakes, Torres et al. (2000), used geotechnical reports and data from various institutes (such as the California Department of Water Resources, and the U.S. Army Corps of Engineers), to identify aspects of levees that make them vulnerable to earthquakes (e.g., presence of loose soils, quality of foundation of the soil, historic performance against quakes and the width of the levees). Data for levees in some areas was unavailable. With the help of in-situ measurements (borings, reports), additional data for these levees was procured. Properties of the influence of river water (level of erosion, seasonal variations of water levels, interaction with tides) were also considered in the assessment. The levees in the San Joaquin Delta were then assigned to four different damage potential zones based on the aforementioned levee and water properties. The probability of a number of levee failures was then evaluated using a levee fragility function, applying the two different models previously mentioned. Different scenarios of earthquakes (intensity, vault of origin, recurrence rate) were then used to evaluate how many potential levee break points could occur (Torres et al. 2000).

While the study of Torres et al. (2000) analyses the vulnerability of levees in depth, it does not investigate the repercussions for the deltas social components. An assessment that focused on social vulnerability due to potential levee failures in the San Joaquin Delta is that of Burton and Cutter (2008).

Burton and Cutter (2008) used the SoVI (Social Vulnerability Index) method from Cutter et al. (2003), with the same socio-economic parameters and parameter selection technique PCA (Principal Component Analysis). The socio-economic parameters used were socio-economic status, race, age, development density, renters, and health care institutions, all per census block. Simultaneously, the inundation risk from possible levee breach sites, was assessed using a U.S. Army Corps of Engineers dataset of levees with maintenance concerns, and a dataset of critical erosion sites (as identified by the California Department of Water Resources). A flood model from FEMA was used to simulate the extent of 100 and 500 year flood zones. Two analyses of variance (ANOVA) tests were performed in order to estimate the social vulnerability in the areas that are at risk to flooding. The assessment concluded that combining social vulnerability with flood risk maps provides a more useful tool for emergency planners to identify areas that are most vulnerable to flood events (Burton and Cutter 2008). A similar assessment that used the SoVI in this way was conducted in the Yangtze River Delta by Chen et al. (2013), although this assessment did not consider anthropogenic mitigation efforts.

Multi-component studies are very rare. Studies such as Cutter et al. (2000) and Kleinosky et al. (2006) can be considered to a certain degree as a multi-component study, but, only the study by IMHEN et al. (2011) can truly be classified as a multi-component study. The study of IMHEN et al. (2011) (the Vietnamese Institute for Meteorology, Hydrology and Environment) focused on the Mekong Delta. A large and multidisciplinary effort, the study considered parameters related to geophysical (geomorphology, precipitation data, temperature, SLR, flooding events, storm surges, salinization, erosion, subsidence), socio-economics (land cover and land use, considering different crop types, fishing activities, industrial activities, energy supply, sewage disposal, water supply, infrastructure, population density, education and unemployment rates), environmental (type of natural area, biodiversity) and anthropogenic mitigation aspects (institutions, dykes, hospital capacity). The vulnerability has been assessed of key sectors in each district, namely: population vulnerability, poverty vulnerability, agriculture and livelihoods vulnerability, industry and energy vulnerability, as well as urban settlements and transportation vulnerability. These key sectors were selected using the Comparative Vulnerability and Risk Assessment (CVRA) methodology, which is based on the IPCC approach of conducting vulnerability assessments. The degree of vulnerability of each district for each of the 5 key sectors is composed of the comparative exposure (to other districts) and by respective sensitivity (of the parameters). The result of the vulnerability assessment shows that the most vulnerable districts in the Mekong River Delta are those with a large population density and inadequate protection from flooding and storms (IMHEN et al. 2011). Contrary to the other major trends of

vulnerability assessments, multi-aspect studies are very detailed and incorporate a lot of information about many, if not all, system components and aspects considered. There are not many of these assessments available, even though these assessments provide the most complete answer to river delta and its system component vulnerability. This is most likely due to the high complexity, highly multidisciplinary nature, and high cost of such assessments.

Processes considered

Coastal river deltas and their ecologic, social, and economic, components, as well as the anthropogenic mitigation efforts (part of the economic component) that protect river deltas, are subject to various natural (such as storms, earthquakes, SLR) and anthropogenic (such as water, soil, air pollution) processes. It can be observed in Fig. 3b that the majority of vulnerability assessments consider natural processes (85 %), and a minority (15 %) consider anthropogenic processes. Assessments that consider natural processes tend to be highly focused, such as Kleinosky et al. (2006) who assess vulnerability to storm surges in the Chesapeake Bay (U.S.), Wang et al. (2012) who assess migrant vulnerability to typhoons, while assessments such as Tri et al. (2013), Özyurt and Ergin (2010), and Woodroffe (2010) are highly focused on vulnerability to SLR in deltas, and assessments such as Torres et al. (2000) and Burton and Cutter (2008) specifically focus on vulnerability of levees (and their hinterlands) to earthquakes.

When analyzing patterns concerning anthropogenic processes considered, it is observed that if assessments consider anthropogenic processes, these are more likely to be semi-focused studies that assess vulnerability to both anthropogenic and natural processes. Cutter et al. (2000) is a good example of such an assessment, as they incorporated different natural and anthropogenic hazards in their vulnerability assessment of the Winhay Bay in South Carolina, U.S. By superimposing different risk zones of hurricane, earthquake, flood, and chemical release (from fixed point source polluters and possible cargo railroad/motorway incidents), hazard zones that are susceptible to these processes were mapped. These hazard zones were developed using existing data (e.g., outputs of flood and hurricane models, seismic activity of the past in the study area). The risk of tornados, drought, hail and wildfires were incorporated too, though the risk of these hazards was made equal for the entire study area (since these phenomena cannot be precisely predicted for a specific location). By overlapping the hazard zones it was possible to determine what areas are more hazardous for the population and objects within them. The hazard zones were superimposed on socio-economic data per census block (local population demographics (age, race, % of females), total population, amount of housing units and average house value). It was then possible to estimate how many people of different demographics were vulnerable to a certain extent to a specific hazard, and to highlight areas that were in need of mitigation efforts if there was a vulnerable population living in a particular hazardous area. To visualize the vulnerability on a map, the natural and anthropogenic hazard risk zones were superimposed on a socio-economic vulnerability map. To ascertain the degree of socio-economic vulnerability per census block, the data of all blocks were compared with one another. The most resilient and the most vulnerable census block was identified, and the other census blocks were ranked. Additionally, data considering infrastructure, crucial buildings (e.g., evacuation centers, public works and emergency services) and evacuation routes were evaluated. This highlighted certain areas where policy makers had to adjust evacuation routes to circumvent crowded areas. The study concluded by suggesting that vulnerability should be assessed at different times of the year and should incorporate more biophysical features (Cutter et al. 2000). Other studies that consider both natural and anthropogenic processes in their assessments are Peiying et al. (1999), Omo-Irabor et al. (2011), Jiang et al. (2011), and Xu et al. (2011).

There are two studies that are an exception to the rule that anthropogenic processes are only considered in conjunction with natural processes, namely Lin et al. (1997), Hang et al. (2009). These are highly focused chemical studies that assess the effect of (ground) water pollution on the vulnerability of local population consuming crops that are irrigated with this water.

Spatial scales

Vulnerability assessments can be conducted at different spatial scales, namely local, regional, and comparative between non-adjacent sites. Coastal river delta vulnerability assessments are generally performed at smaller spatial scales, i.e., focusing specifically on a single delta. 88 % of the assessments in this review have focused on one delta only, as can be seen in Fig. 3c. When vulnerability is assessed at a local scale, local phenomena within the delta become more important, and studies have the chance to be very specialized in analyzing the vulnerability for the delta in question. Good examples of local assessments are IMHEN et al. (2011), Torres et al. (2000), and El-Raey (1997), which focus on very specific and local aspects and phenomena.

Assessments performed at a larger, regional spatial scale are generally coarser, observing general trends rather than local phenomena (McLaughlin and Cooper 2010). 6 % of all assessments consider not only a specific river delta, but also the coastal region around them, and fall in this category. Good examples are the assessments by Thatcher et al. (2013) of the Mississippi River Delta and surrounding areas; Rao et al. (2009) of the Krishna and Godavari River Deltas (India) and their surrounding areas; Li and Li (2011) of the Pearl River

Delta (China) and surrounding areas; and Shi et al. (2000) of the Yangtze River Delta and surrounding areas. All of these assessments have adapted and adjusted the CVI methodology, while displaying their vulnerability results as smart-lines, i.e., lines parallel to the coast that indicate the rate of vulnerability, focusing on the coastline and not on the inland areas (except per district area in case socio-economic aspects are considered). Local phenomena or aspects of the delta at specific inland locations may become underrepresented in this case.

Besides local and regional vulnerability studies, there are also three comparative assessments, where the vulnerability of various deltaic sites throughout a continent or whole world is assessed and compared. However, these comparative vulnerability assessments have nothing in common in terms of approach, result, or data used, making it impossible to distinguish trends. This makes comparative vulnerability assessments difficult to perform, since for an accurate measurement, data for all parameters should be available. Each of the three comparative vulnerability assessments reviewed have dealt with this inherent problem of comparative vulnerability assessment in different ways. While the assessment of Woodroffe (2010) was limited to a few datasets (population density and elevation), the datasets were available for all deltas (Indus, Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, Red, Pearl, Changjiang (Yangtze), and Huanghe (Yellow)) in question and thus a comparison in degrees of vulnerability could be made. For the assessment of 10 river deltas (Nile, Incomati, Ganges-Brahmaputra, Yangtze, Ciliwung, Mekong, Rhine-Meuse, Danube, California Bay, and Mississippi) by Bucx et al. (2010), geophysical (SLR, erosion, subsidence), socio-economic (rate of urbanization, GDP, people living in risk areas), environmental (wetland condition, ecological measures), anthropogenic mitigation (levees, shelter availability, technological developments in civil engineering, energy facilities), and politico-administrative aspects (type of government, risk prevention plans, regulations) have been considered. In order to compare the vulnerability of each delta, a scorecard was created for each delta based on the summary of the descriptions. Each scorecard was divided into 4 groups: occupation layer, network layer, base layer and governance. Each of the 4 groups then received a resilience score on a 5 point scale (very good-medium-very low) (Bucx et al. 2010). Vermaat and Eleveld (2012) have extracted 21 parameters (such as GDP, coastal slope, SLR rates, geomorphology, dyke height, river discharge, and population density) from the World Delta Database, to assess the vulnerability of 33 deltas around the world (Burdekin, Chao Phraya, Danube, Dneiper, Ebro, Fly, Ganges-Brahmaputra, Godavari, Huang He (Yellow), Indus, Irrawaddy, Krishna, Lena, MacKenzie, Magdalena, Mahakam, Mahanadi, Mangoky, Mekong, Mississippi, Niger, Nile, Orinoco, Parana, Pechora, Po, Red, Sao Francisco, Senegal, Shatt el Arab, Yangtze-Kiang, Yukon,

and the Zambezi River Delta). These parameters are filtered with a PCA. The results can be used to compare the vulnerability for each delta and recommended suitable adaption policies. Furthermore, an analysis of dependence was conducted on two parameters that explain forcing factors; land lost and people at risk of being flooded. It was concluded that the increase of vulnerability in river deltas is not only a result of a changing climate and SLR, but also due to the increase of population and wealth in these areas, and upstream activities (especially river dams) restricting sediment flow to deltas (Vermaat and Eleveld 2012).

Temporal scales

While most coastal river delta area assessments assess the degree of vulnerability at the 'current' moment (77 %, see Fig. 3d), there are also a few assessments (23 %) that tracked the change of vulnerability degree over time. These studies are Suanez and Bruzzi (1999), Frihy (2003), Huang et al. (2004), Jiang et al. (2005), Khang et al. (2008), IMHEN et al. (2011), Wang et al. (2011a), Fatorić and Chelleri (2012), Rasul et al. (2012), Vermaat and Eleveld (2012), and Liu et al. (2013). These studies contain multi-temporal datasets (such as future SLR estimates, tidal gauge records, census data, or EO data of different years) and use these to estimate the changes in vulnerability degrees or the extrapolation of vulnerability for various future scenarios. This is also the case in the assessment of social vulnerability by Ge et al. (2013) of the Yangtze River Delta in China. Nine socio-economic parameters were used for this study, namely: population growth, percentage of rural and urban population, regional per capita GDP, average household size, percentage of females, GDP per square kilometer, investment in fixed assets per square kilometer, per capita income, and the number of hospital beds per 1000 inhabitants. The parameters were extracted from Chinese census data and normalized so they could be combined to calculate the social vulnerability using a PPC (projection pursuit cluster) model. This model is a technique used to seek out a linear projection of multivariate data, where the projection index is computed on a dataset. The PPC method is designed to reveal clustering characteristics in multivariate high dimensional data. Eventually, the social vulnerability of the study area for the years 1995, 2000, 2005, and 2009 was calculated. The results, generalized per county, show that during this time span the social vulnerability decreased in the Yangtze River Delta (Ge et al. 2013).

Methodical characteristics of river delta vulnerability studies

The review results of all methodical characteristics can be found in Fig. 4. These results are discussed for each individual characteristic in the following sub-sections.
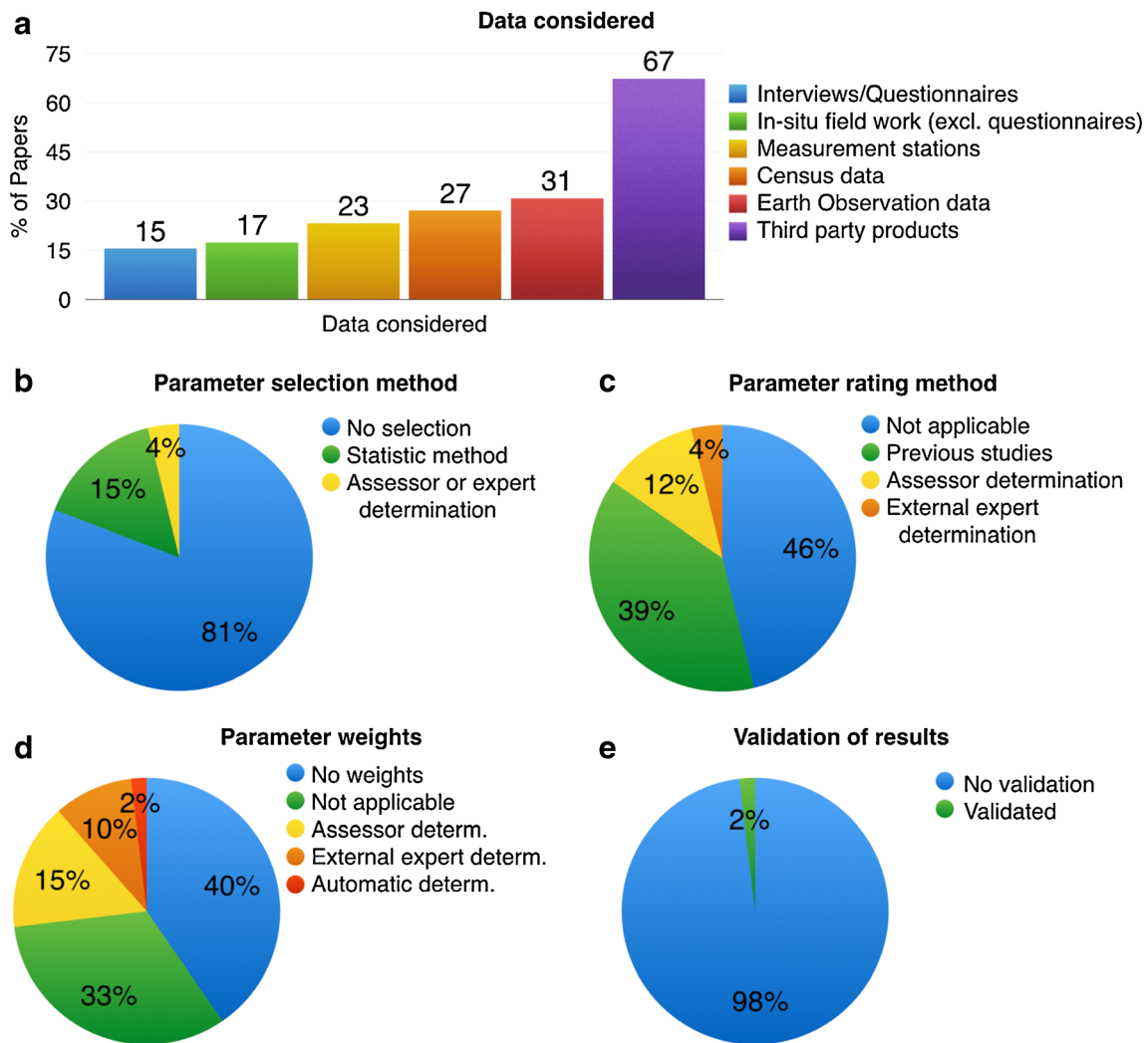
Fig. 4 Classification and categorization results of the coastal river delta vulnerability assessments for each of the methodical characteristics

Data considered

The goal of vulnerability assessments is to visualize which system components at which location are vulnerable to internal or external processes. Afterwards, mitigation efforts may be proposed or implemented that help to reduce the degree of vulnerability. Therefore, the best assessments are issue driven: assess which internal and external processes and threats affect the river delta and its system components, assess the impact and extent of these processes and threats on which specific system components, assess the coping and adaptive capacity of each system component to counteract the negative effects caused by these processes and threats, and finally, assess the net result of the negative impacts vs. coping and adaptive capacity of each system component, thereby determining the rate of vulnerability or resilience of each system component. Such an issue driven analyses can highlight the (potential) weak points in the river delta system. However, constraints

in financial resources to acquire (reliable) data, or the lack of data altogether, means that vulnerability assessments are often data driven. This means that often data availability determines the extent of the assessment. Choosing the right data sources is important for vulnerability assessments, as each data type has different strengths and weaknesses. Five different data types have been distinguished for this review, namely: census data, household surveys, field work data, data from measuring stations, and remote sensing Earth Observation (EO) data. These are categorized results as assessments can use a wide variety of data.

The results of the analyses on the data that was considered are presented in Fig. 4a. Please note that – just like for the "Delta components considered" in the "General characteristics" section, for the "Data considered" section the different types of data used could add up to more than 100 %, as several studies used multiple types of data with equal weight, and therefore were assigned to two, three, or

more data types. As can be seen in Fig. 4a, the most popular dataset used by vulnerability assessments are products from third parties. These are datasets generated by other researchers. Third party data is generally used in assessments when raw data is not available. It enables assessors to assess and compare the vulnerability of various deltas across the world with homogenous datasets. Results of previous studies, or open data products (e.g., population density grids, land use maps) from institutions such as the World Bank, Food and Agriculture Organization of the United Nations (FAO), WWF, National Aeronautics and Space Administration (NASA), or others can be used. The latter is demonstrated by studies such as Vermaat and Eleveld (2012).

EO data comes in second place, with 31 % of the assessments using it (Fig. 4a). Vulnerability assessments use satellite images, specifically either multispectral data or radar data (often in the form of Digital Elevation Models, DEMs). The uses of EO data are aplenty, and the data itself does not suffer from bias, although the analysis and complexity of processing of this data might be subjected to some bias or simplification. The potential of EO data has not yet been fully exploited by vulnerability assessors, except for two main trend of usage: LULC (Land Use Land Cover) map generation with multispectral data, and shoreline analysis with SRTM digital elevation models. Exceptions to these trends are the studies by Jiang et al. (2005), and Xu et al. (2011), who have also used multispectral satellite imagery to assess wetland vigor, and Wang et al. (2011a), who has combined LULC mapping with a spatial habitat fragmentation mapping analysis over multiple years. Examples of assessments that use multispectral EO data for LULC purposes are Jiang et al. (2005), Kleinosky et al. (2006), Rao et al. (2009), De Andrade et al. (2010), IMHEN et al. (2011), Xu et al. (2011), and El-Raey et al. (1997). Examples of assessments that use EO data for shoreline change rate estimation are Frihy et al. (2010), Elewa et al. (2012). Assessments that used EO DEM data are Mount and Twiss (2005), Rao et al. (2009), Woodroffe (2010), Gesch (2013), Liersch et al. (2013), and IMHEN et al. (2011). A good example of an assessment that uses a wide variety of EO data is Boori et al. (2010), who used Landsat TM (Thematic Mapper), ETM+ (Landsat Enhanced Thematic Mapper Plus), SPOT 4-HRVIR (Satellite Pour l'Observation de la Terre, Satellite for Earth Observation, High Resolution Visible Infrared), Ikonos, CBERS 2B (China–Brazil Earth Resources Satellite 2B), and SRTM (Shuttle Radar Topography Mission) data to identify shoreline change rate, LULC, and coastal slope for the Apodi River estuary (Brazil). Additional third party data for the mean tidal, wave height, and mean SLR has also been incorporated, as well as 20 sample sites along the coast to identify geomorphology. Finally, the CVI method was used to estimate the coastal vulnerability. An inundation map (made with the SRTM data with different SLR scenarios) has been overlaid with an LULC map, infrastructure data, and settlement data, to highlight areas that are at risk of inundation along the Apodi River (Boori et al. 2010).

Census data is used by 27 % of the vulnerability assessments (see Fig. 4a). These are predominantly the studies that are conducted in developed countries that have accessible census data and focus on socio-economic aspects. Studies that consider socio-economic aspects but do not have access to census data are more reliant on third party databases. Census data is widely available in developed countries, contains much data about socio-economic system components, and is easily converted to parameters for vulnerability assessments. In most cases, census data is acquired in regular intervals so it can be used to analyze trends over long periods of time. The quality of census data is dependent on the size and delineation of census block borders (which may not correspond to the delineation of the river delta), and the interview method to acquire the census data might not be reliable in all countries. Also, since it is tempting to use many parameters from census data, these parameters might be highly correlated. Reducing large amounts of parameters from census data through parameter selection methods is a common trend. Examples of assessments that use census data are the highly social focused studies elucidated earlier, such as Cutter et al. (2000), Burton and Cutter (2008), Chen et al. (2013), Ge et al. (2013), and Rygel et al. (2006). Rygel et al. (2006) discussed the aspect of social vulnerability in the Chesapeake Bay (U.S.). A PCA has been used to evaluate 57 different socio-economic parameters (derived from U.S. various census data per U.S. census block group). The assessors found thirteen socio-economic parameters (relating to poverty, gender, race, age, and disability) combined to be responsible for the highest variance in the dataset. However, they eventually incorporated three parameters in the assessment (poverty, immigrants, old age/disabilities), since these three had a significantly larger contribution to the variance as compared to the remaining ten parameters. They employed a multi-objective optimization analysis with a pareto ranking method to rank these three social parameters for each census block in the study area, as the contribution of each parameter is different for each block. These rankings were then compared with all other census blocks in the study area. Eventually, 19 different pareto ranks were identified, showing the final relative vulnerability of each block compared to other blocks in the study area, thus highlighting the areas that need attention (Kleinosky et al. 2006; Rygel et al. 2006).

Surveys amongst households, experts, or stakeholders may provide a detailed insight in the workings, policy, concerns, gains, and losses of the socio-economic components of deltas. Such data may not be revealed through other means (such as the use of census data), and can therefore only be extracted using these surveys, which are generally time consuming and very costly. The quality of such surveys depends on the robustness of the questionnaire, sampling scheme, method and skill of the interviewer, and the honesty of the interviewee. It is

observed that 15 % (Fig. 4a) of the vulnerability assessments use surveys. IMHEN et al. (2011), Fatorić and Chelleri (2012) are the only assessments that considers stakeholder consultations to gather data about the Mekong River Delta, Ebro River Delta (Spain). The others use household surveys to analyze the (perceived) vulnerability of local households. Household surveys are predominantly used in developing countries where census data is not available. The assessments of Ologunorisa (2004), Wilk and Kgathi (2007), Clement (2013), and Mmom and Aifesehi (2013), which use household surveys extensively, are all conducted in Sub-Saharan Africa), or where insufficient census data is available for a certain demographic or topic, which is the case of Wang et al. (2012) (migrant workers in the Yangtze River Delta), and De Andrade et al. (2010). De Andrade et al. (2010) assessed the vulnerability of the San Marcos Bay (Brazil) of various biota, as well as the livelihoods of the local fishing population that depend on it, to oil spills. These oil spills originate from the Itaqui-Bacanga port complex. Using high resolution EO data, the location and type of geomorphological units were assessed. Further parameters included concern the relation between socio economic parameters (education, income), and fishing activities using 187 questionnaires among the local population. The parameters were given a unit independent rating by the assessors through distinguishing three levels of vulnerability (high, medium, low) of the natural and social vulnerability. The parameters were then averaged and compiled in three vulnerability indices: environmental vulnerability, socio-economic vulnerability and total vulnerability (De Andrade et al. 2010).

Twenty-three percent of the vulnerability assessments used data from measurement stations (see Fig. 4a), all of which use tidal gauge data, such as Frihy et al. (2010), Boori et al. (2010), and Marriner et al. (2013). Using the results of previous studies as well as data from 105 core samples, Marriner et al. (2013) investigated the rate of subsidence of the Nile River Delta. The assessment used tide gauge data and sediment discharge data to estimate the degree of vulnerability of the delta due to upstream anthropogenic influences (most notably the construction of the Aswan dam). The assessors concluded that the long history of human construction in the delta (such as levees and redirection of streams), as well as increased exploitation of natural resources in the delta, the dam construction upstream, and the weakening Ethiopian monsoon lead to increasing subsidence rates in the delta. These processes make the delta more vulnerable to SLR (Marriner et al. 2013).

17 % of the vulnerability assessments used in-situ measurement data (Fig. 4a. Highly focused studies that focus on soil chemistry properties, such as Lin et al. (1997) and the previously mentioned Hang et al. (2009) use predominantly in-situ measurements as this is the only method such data can be acquired. Others have used in-situ datasets to acquire a greater

insight in the geophysical properties of a study area, such as Frihy and El-Sayed (2013). The focus of Frihy and El-Sayed (2013) was the vulnerability to RSLR of social and economic activities in the Nile River delta, using a variety of data, such as transects (detailing geomorphologic aspects of the coast), a digitized topographic map (for elevation data of the study area (Frihy 2003)), census data (for socio-economic parameters such as population density, economic activity), in-situ measurement data (to identify and locate coastal protection infrastructure (Frihy 2003)), core samples (to estimate subsidence in the study area), measurement stations (for measuring tide gauge in different areas of the study area to identify spatial variability (Frihy et al. 2010)), and data as extracted from previous/other literature or assessments, such as soil accretion and erosion rates (extracted through EO data), predicted changes in sea level, tectonic faults and earthquake locations and severity. The vulnerability of the coastline and the inland areas of the Nile River delta and its surrounding Mediterranean coastal sections were then ranked in a scorecard as high, moderate, and low, only during extreme events, or areas that are safe. This ranking has been performed for a variety of coastal features and locations within those sections (Frihy 2003; Frihy et al. 2010; Frihy and El-Sayed 2013).

Parameter selection method

When large amounts of highly correlated parameters are added in vulnerability assessments, it may be that certain processes or aspects are overrepresented compared to other processes. To avoid this, studies that consider a lot of parameters select certain parameters either through expert guidance or statistical selection methods. As can be seen in Fig. 4b however, only 15 % of all vulnerability assessments have used a statistical selection method. PCA is by far the most popular parameter selection method, used by Burton and Cutter (2008), Chen et al. (2013), Kleinosky et al. (2006), Rygel et al. (2006), Vermaat and Eleveld (2012), Wilk and Kgathi (2007), and Xu et al. (2011). Ge et al. (2013) uses a PPC method. Statistical parameter selection methods have only been used by studies that use a plethora of census data in their assessment. The majority of studies (81 %) did not use any selection method. This is mostly due to the lack of data available to add more parameters to vulnerability assessments. However, two assessments, namely Li et al. (2012) and Suanez and Bruzzi (1999) relied on experts or previous assessments which parameters to use in their vulnerability assessment, without adding any others, but using their own datasets to populate those parameters.

Parameter unit independent rating method

Once the parameters are selected, they have to be ranked or converted to a non-dimensional number before vulnerability

can be assessed by means of a vulnerability index (i.e., a mathematical equation to estimate the degree of vulnerability). The majority of assessments did not utilize a unit independent rating method for vulnerability assessments (46 %, see also Fig. 4c). Some studies, such as the aforementioned Bucx et al. (2010) compared the influence on vulnerability by different processes using a scoring system to determine vulnerability of the study areas. Others, such as the previously elucidated Frihy (2003) combined all parameters and discussed, rather than use a mathematical approach, to calculate the degree of vulnerability. 39 % of vulnerability assessments refer to previous studies when it came to the rating of parameters. This was especially the case when the vulnerability assessment methodology is based on the popular CVI methodology. 12 % of assessors used a rating scheme which they devised, or adapted to fit local situations. Such assessments include the aforementioned study of Boori et al. (2010). Lastly, there are two studies that used experts to determine the unit independent rating method; Li et al. (2012) and Torres et al. (2000).

Parameter weighting method

When combining the non-dimensional parameters in a vulnerability index, some assessments choose to append an additional weight to specific parameters in order to emphasize or depreciate them. Using parameter weights is contested, as there is often no scientific underpinning to favor specific parameters over others (Cutter et al. 2003; Fekete 2010; Özyurt and Ergin 2010). As a result, the majority of vulnerability assessments reviewed here (40 %, see Fig. 4d) do not use any parameter weights. However, not attributing any weights and simply averaging the used parameters means assuming all parameters are equally important, something which may be unrealistic. There are however different methods to add weights to parameters in a vulnerability index. In our review, this is demonstrated by several vulnerability assessments through PPC, demonstrated by Ge et al. (2013); and AHP (Analytical Hierarchy Processing), demonstrated by Xu et al. (2011), and Li et al. (2012). The PPC method avoids the researchers attributing their own weights by mathematically calculating the relevance of each parameter automatically, while the AHP method relies on several experts expressing the importance of one parameter over other ones (a priori knowledge). The study by Li et al. (2012) of the Yangtze River Delta assessed its vulnerability to erosion using 13 parameters (coastal elevation, coastal slope, shoreline change rate, tidal range, significant wave height, RSLR, intertidal width, intertidal vegetation type and width, population density, land use type and ecological hotspots). The usage of these parameters has been recommended by experts and previous assessments. The parameters were derived using EO data, nautical charts, wave models, and the gridded population of the world dataset (Gridded Population of the World, GPWv3). The parameters were made unit independent by ranking different thresholds between 1 and 5. Using the AHP method, experts ranked the parameters by level of priority, after which the parameter weights were calculated. The vulnerability index was then calculated as the weighted sum of the parameters (a dimensionless result), rescaled and visualized different colors of a line conform to the coastline. The results show that the Yangtze River Delta area is very vulnerable to coastal erosion, however the lack of data limits the reliability of the vulnerability assessment (Li et al. 2012).

Validation method

Validation methods are only rarely conducted in vulnerability assessments (as the classification result shows in Fig. 4e). The only vulnerability assessment which attempted to validate their results is the previously highlighted assessment by Ge et al. (2013). In order to validate the vulnerability results of all 4 time intervals, an annual disaster index (calculated by dividing the yearly economic losses by the total exposed area for each year) was completed at a provincial scale for the study area. The results of the disaster index were then compared with the SVI results for each year between 1995 and 2009. A comparison of the two results showed that the social vulnerability decreased, 'confirmed' by the disaster index, which showed that over time the losses decreased as well. This validation was only conducted on a provincial scale, and not a local scale, due to lack of available data (Ge et al. 2013).

Discussion

The main observation of this review is that highly focused (e.g., focus is on one particular component or one particular process) vulnerability assessments clearly make up the majority of all assessments analyzed. A typical vulnerability assessment – for example – focused on the ecologic component of the delta exclusively, and in this context deals with the vulnerability of the delta systems towards the process of sea level rise. Furthermore, a few studies investigate the vulnerability of two to three of the delta's components (ecologic, social, and economic) while they still focus on just one of the processes and threats (e.g., vulnerability of cities and economic infrastructure to sea level rise). Very few investigations consider all three delta components whilst at the same time addressing multiple processes. Such multi-focal analyses are in the vast minority and only make up a handful of studies.

A large challenge with the topic of river delta vulnerability in general, as well as with this review undertaken, is the fact that firstly, river delta environments are highly complex and dynamic systems, that secondly, vulnerability itself is a term that is open to interpretation, and that thirdly, studies published in this context are very diverse with respect to their

general and methodical characteristics. This complicates the comparison of studies, as well as the recommendation of the development of a "standardized" blue print framework for future river delta vulnerability assessments. Based on the categorization and classification of vulnerability assessments undertaken for this review, it could be observed that single-component, single-process studies are outnumbering other studies, while multiple-component, multiple-process studies would be best-suited to represent the intricacy of river deltas and their components affected by a large number of internal and external processes and threats. Numerous studies underline in their discussion that multiple-component or multiple-process studies – or even both combined – would be a value-adding extension of their presented study. However, the undertaking of such complex studies are usually hampered in their realization by a lack of suitable data, a lack of (timely, monetary, staff) resources, as well as the fact that a very cross-sectorial approach would be needed in this case. Multi-component, multi-process studies would need researchers form the natural sciences, engineering science, as well as social and economic sciences to work together, which can usually only be realized in very large trans-disciplinary research networks or projects. Several authors, such as Gornitz et al. (1994); Cutter et al. (2000), (2003); Thatcher et al. (2013), and Kuenzer and Renaud (2012) have likewise underlined this need. However, cross-sectorial, trans-disciplinary studies face the challenge that different scientific disciplines define vulnerability in a different way. Patt et al. (2010) even discussed that attuned definitions of vulnerability are sometimes used as a justification to implement extensive mitigation efforts (Patt et al. 2010). It is therefore of highest relevance for multi-component, multi-process assessments that a clear definition of vulnerability and related terms for coastal river delta systems are used and agreed upon before such a study is conducted. Good examples, approximating this desired approach have been presented by IMHEN et al. (2011); Cutter et al. (2000), and Kleinosky et al. (2006) amongst others.

A further challenge with vulnerability studies is the fact that different researchers – even from the same field and discipline – apply different methodologies to derived vulnerability, and create different sets of parameters, as well as parameter weights to arrive at the final vulnerability estimate. As an example, while there are numerous geophysical studies on the market that address ecological river delta vulnerability to sea level rise, the pathways and approaches taken to create a vulnerability representation (spatial map, coastal vulnerability line) vary greatly. Some vulnerability assessments reviewed, especially those that use the Coastal Vulnerability Index (CVI) derivatives, compile parameters of various aspects in one index, after which vulnerability is presented as a unitless vulnerability score or degree. However, if the number of parameters selected to assess the vulnerability of each river delta component (ecologic, social, economic) is not the same (as

is often the case with an abundance of socio-economic parameters extracted from census data, opposed to few parameters extracted pertaining to ecologic parameters), this leads to an over- or underrepresentation of certain parameters. Even if an equal amount of parameters is considered, in reality the importance of each parameter is rarely the same. While a solution to this problem could be approximated through the use of various intricate parameter selection methods, unit independent rating methods, and weighting methods, it still remains a challenge to prove that such results have a higher quality or are more valid than others.

This actually is the root of the problem with vulnerability assessments: it is near impossible to qualitatively or quantitatively validate them against any kind of ground truth. Whereas – for example – researchers mapping water quality from space based on Earth Observation (EO) data can validate their spatial maps against local in-situ water quality measurements, a vulnerability researcher has no way to compare its unitless vulnerability maps or coastal vulnerability lines against any other type of data. The only possible way to validate vulnerability is an extremely unlikely scenario: a researcher would have to undertake a vulnerability study for a certain area with respect to a certain process or threat, which then actually occurs, after the assessment has been conducted. For example, if a research group assesses a river delta's vulnerability to a possible tsunami, and then the tsunami occurs in exactly the locality and with the exact magnitude that the researchers assumed (a few months after the assessment, and assuming, that no mitigation efforts have been undertaken by stakeholders in the delta to buffer the system against an event in the meanwhile), it would – theoretically speaking – be possible to then validate the vulnerability results in retrospect. However, this scenario is extremely unlikely and no publication presents such a case. Nevertheless, there are researchers who have tried to indirectly validate their vulnerability assessments based on past hazard events (Ge et al. 2013) this approach is actually not a true validation, as the pure knowledge about these past hazard events will already influence the design of the vulnerability assessment itself, so that bias is involved.

Another outcome of the review analyses is that - obviously - the availability of data strongly impacts the vulnerability assessment. Whereas most authors have in depth field knowledge of their area of interest and have a desire to conduct an issue driven assessment, a limited amount of usable and reliable data (spatial data, statistical data etc.) might still hamper the assessments' overall process. Missing data and constraints in resources to acquire data (in-situ surveys, spatial data, etc.) are usually the main hindrance to come up with a holistic, complex vulnerability quantification. This is especially true for deltas in developing and emerging countries where data might be classified, unreliable, has a low spatial resolution, or is simply not available. A further problem of data acquisition

arises in river delta areas, which are hard to access (also in-situ) due to safety concerns. For example, even if (monetary and staff) resources for in-situ data collection would be available, it is hard to perform such tasks in countries with civil war, or extremely unsafe conditions (e.g., Niger Delta). Furthermore, some areas are very inaccessible, as infrastructure does not exist. Researchers rarely have all the amount of data available that they would like to have in an optimal case. Census data, economic and further statistical data may furthermore hold the problem of questionable data reliability, depending on the country or area of origin, and a coarse spatial resolution which limits the data's accurate representation in river deltas. This challenge of reliability and bias also comes with data acquired during household surveys or field campaigns – especially if such data has been collected by different individuals, at different times.

Here, remote sensing EO data can play an important role as one possible source of globally available, spatial, unbiased data. About 30 % of the studies analyzed utilized EO data within their vulnerability assessment, but the full potential of this data is rarely exploited fully. While numerous assessments integrate land cover and land use maps derived from EO data into their studies, or some authors include information on shoreline changes derived from EO data, the inclusion of other EO derived information products and parameters is rare. Kuenzer et al. (2014b) have addressed the fact that a large amount of EO data is freely available in satellite data archives globally, but that – at the same time – data and products usage is often still hampered by the fact that EO scientists do not necessarily "speak the language" of other science branches, and that the provided EO data is hard to be employed by researchers, who are not remote sensing experts. Advantages of EO data are that observations of a distinct location are usually available multiple times per year. Especially, data of sensors such as Landsat (available since the mid of the 1970s, free of charge, 30 m resolution) enables to investigate the dynamics of a locality at dense, timely intervals. A resolution of 30 m enables the derivation of detailed land cover and land use maps, the extraction of coastlines, the identification of larger pollution sources, the analyses of flooding and inundation, degradation processes, ecosystem fragmentation rates, and many more. Also the European Sentinel sensors, which are currently being launched, enable weekly observations of every space on our planet (except the poles) at a high (up to 5 m) resolution. Furthermore, this data is available free of charge to the science community. For further information of data, products, and their temporal and spatial coverage and availability, the reader is referred to Kuenzer et al. (2014b). Depending on the method of the analysis and the goals of the vulnerability assessment, EO data can provide accurate, multi-temporal data of physical properties of biotic and abiotic components in the study area. Especially the fusion and joint analyses of census data, household surveys, in-situ studies, and

measurement station derived data with EO or geospatial data can compensate for the shortcomings of other data types (such as resolution, quality, reliability). Using a vulnerability index to estimate ecologic, social, or economic degrees of vulnerability in an aggregated, spatial map furthermore provides a clear visual impression of the varying degrees of vulnerability of river delta components. Multi-temporal studies including EO data additionally allow for the investigation of vulnerability over time, which can reveal not only the dynamics of an area, but possibly also the effectiveness of previously implemented mitigation efforts.

Last but not least vulnerability studies published in scientific journals usually do not address the fact if – or if not – the vulnerability results have been represented to stakeholders and decision makers or the locally affected people, or had an impact in the area investigated. After all, each vulnerability assessment should be the starting point for mitigation efforts to increase the short-term coping capacity, as well as the long-term adaptive capacity of the river delta's ecologic, social, or economic component. As mentioned above, vulnerability assessments are extremely complex in nature, and definitely pose a large challenge to communicate the outcomes of such studies to non-scientists in a transparent and convincing manner. Here, spatial maps, which visualize the degree of vulnerability in easy to understand color schemes might be much preferred to complex tables with a large amount of number products derived from complex mathematical operations. A close dialogue between scientists, politicians, decision makers, and people implementing mitigation measured is needed even during the design of the vulnerability assessment, to ensure that results might unravel their value in the "real world" rather than remaining a scientific exercise.

Conclusion

Coastal river deltas and their ecological, social, and economic components are intricate and highly dynamic systems, exposed to and affected by numerous processes and threats arising from within the delta itself, as well as from localities outside of the delta. Internal processes and threats such as urban sprawl accompanied by water-, air-, and soil pollution, resource extraction related ground subsidence, as well as the loss of biodiversity-rich habitats due to the expansion of agri- or aquaculture are just some examples of the processes impacting delta vulnerability, which arise from within the area. Upstream water diversion, sediment depletion by hydro-power dams, storms, as well as algae blooms or larger oil spills are just some examples of processes, which may arise from outside the delta, but still impact the delta's vulnerability to a large extent. The extreme complexity, and high dynamics of deltas, the large variety of processes impacting these localities, as well as the fact that most deltas are densely populated areas

of strategic economic importance, makes coastal river deltas hotspots of vulnerability. The main goal of this study has been to review, categorize and classify coastal river delta vulnerability assessments, to reveal patterns with respect to the general characteristics addressed by these studies, as well as the methodical approaches selected by the individual assessments. All studies were analyzed with respect to the main components addressed for the respective delta (the ecologic, social, or economic component, either singular, or a several of these three), the processes considered (processes and threats of natural versus anthropogenic origin), the spatial scale of the assessment (local, regional, global/comparative), as well as – last but not least – the temporal scale of the study (uni-temporal versus multi-temporal). Furthermore, all studies were categorized depending on their methodical properties, depending on the data used (e.g., household interviews, measurement station data, in-situ field data collection, census data, third party products and Earth Observation (EO) data) as well as the parameter selection method, the parameter rating methods, parameter weights, as well as the validation of the vulnerability assessment. The following conclusions can be drawn based on the in-depth analysis of all river delta vulnerability studies reviewed:

- Coastal river deltas are highly dynamic and complex systems, but are also very diverse in terms of location (geographic/climate zones, as well as developed, emerging, and developing countries), extent (size), complexity of the ecologic, social, and economic delta components and their relevance, as well as the natural and anthropogenic processes and threats from internal or external sources that affect these delta components. These factors alone already complicate the comparability of river deltas globally. Additionally, the concepts of vulnerability and related components are subject to varying degrees of interpretation, and a strict definition or blue-print framework for vulnerability assessments does not exist. This makes the comparison, evaluation, and categorization of river delta related vulnerability assessments a very complex and demanding task.

- The vast majority of vulnerability assessments investigated are highly focused studies, addressing one specific delta component (either the ecologic, or the social, or the economic), as well as just one process affecting this specific component (e.g., sea level rise). Multi-component, multi-process vulnerability studies are rare, which is understandable considering the large amount cross-sectorial research work and of multi-disciplinary base data needed to conduct such an assessment. However, multi-component, multi-process assessments present a more comprehensive evaluation of the location under investigation and reveal more information about the degree of vulnerability in the respective delta.

- It is furthermore striking that most assessments focus on natural processes (e.g., impact of a storm on the ecologic component of the delta), whereas studies that put anthropogenic processes into the foreground are rare (e.g., vulnerability of the local population to toxic waste waters etc.). Reason for this is probably the complexity of these anthropogenic processes and the difficulty of obtaining sufficient data to quantify these processes. However, since many coastal river delta areas are hotspots of socio-economic development such processes should be considered more often. Even under the absence of suitable data, simple buffer operations (distance to factories/nuclear plant etc.) might help to approximate the derivation of zones with differing vulnerability.

- Concerning the spatial and temporal component of delta vulnerability studies most assessments present local (one delta) and uni-temporal (one point in time) analyses of the respective delta. This is related to the vast complexity of vulnerability derivation and comparison, whilst adhering to defined research time frames. Furthermore, partially limited data availability does not ease this situation. However, studies conducted on a regional scale (national, continental), or assessments that compare the status of various deltas with comparable attributes globally, may provide further insight for researchers, stakeholders, and policy makers to discover possible mitigation pathways based on "lessons learned" from other deltas. Although uni-temporal studies are most common, conducting multi-temporal assessments of vulnerability may potentially aid decision makers to evaluate the effects of mitigation efforts, study changes of vulnerability degrees, and identify possible causes of vulnerability increase.

- Limitations in data availability and reliability, as well as the resource intensive nature of gathering in-situ data or to conduct surveys, have great impacts on vulnerability assessments. The potential of spatially representative and unbiased EO data has been explored by about one third of the studies analyzed. Using EO data definitely supports vulnerability assessments, because of the advantage to observe an area at different spatial resolutions, with different types of sensors, allowing the derivation of different types of information products (land cover, land use, inundation, coastlines etc.). However, despite the fact that a large amount of EO data is freely available in global archives, the potential of this data source is not fully unlocked yet, and further integration of integrating EO data in vulnerability studies should be recommended. In this context, also the remote sensing community needs to ensure that the data and information products made available can be understood, handled, and processed further by researchers of other disciplines.

- Methods of parameter selection, ranking, and weighting are manifold and underlie a strong analyst

influence. The review shows that a majority of studies rely heavily on expert opinions or previous studies. In many vulnerability assessment several parameters are needed to retrieve the final vulnerability degree, and these parameters are weighted based on the analysts focus (e.g., if parameters such as distance of living to the coast, terrain elevation and mobility define a person's vulnerability to a tsunami event, it is up to the analyst to define how strongly he weights one or the other parameters to arrive at the final vulnerability degree). It complicates the comparability of studies that standardized methods, pathways, or even blue print type of frameworks for the derivation of river delta vulnerability do not exist – although an urgent demand for this became obvious through this review. Furthermore, vulnerability results can currently not be validated, as vulnerability "ground truth" does not exist. While we discussed possible indirect ways to validate vulnerability assessment, even these are hard to put into practice. It is therefore likely that the ambiguous nature of vulnerability studies cannot be resolved. This, however, does not decrease the value of such studies, which attempt to quantify complex processes, and are often good examples of urgently needed cross-sectorial research between the natural and the social sciences.

- Only one of over 50 studies analyzed mentioned the stakeholder group, for which the respective vulnerability assessment has been undertaken. It is therefore unclear, if most of the studies, are purely scientifically motivated, or if communication with decision makers has taken place. Nevertheless, communicating vulnerability results in a transparent manner to stakeholders, policy makers, and the local population should be a crucial aspect. The addressee of an assessment actually is majorly defining how vulnerability outcomes need to be presented to be understood. In general, the production of spatial maps, which are easy to understand (compared to complex tables of numbers based on intricate mathematical formulas) will support the successful communication of results to a wider audience. Furthermore, studies could benefit from communicating "user requirements" that existed prior to the vulnerability assessment, which have impacted the focus of the study.

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