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Review

A framework for integrating ecosystem services indicators into vulnerability and risk assessments of deltaic social-ecological systems

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ABSTRACT

Due to increasing population pressure and urbanization, as well as global climate change impacts, many coastal river deltas are experiencing increased exposure, vulnerability and risks linked to natural hazards. Mapping the vulnerability and risk profiles of deltas is critical for developing preparedness, mitigation and adaptation policies and strategies. Current vulnerability and risk assessments focus predominantly on social factors, and typically, do not systematically incorporate a social-ecological systems perspective, which can lead to incomplete assessments. We argue that ecosystem services, which link both ecosystem functions and human well-being, can be used to better characterize the mutual dependencies between society and the environment within risk assessment frameworks. Thus, building on existing vulnerability and risk assessment frameworks, we propose a revised indicator-based framework for social-ecological systems of coastal delta environments, supported by a list of ecosystem service indicators that were identified using a systematic literature review. This improved framework is an effective tool to address the vulnerability and risk in coastal deltas, enabling the assessment of multi-hazard risks to social-ecological systems within and across coastal deltas and allows more targeted development of management measures and policies aimed at reducing risks from natural hazards.

1. Introduction

Coastal river deltas are naturally formed, low-lying landforms that rely on continuous sediment supply to stabilize and balance the coastline (Anthony et al., 2015; Kuenzer and Renaud, 2012). These environments play a central role in food production and water security due to the highly dynamic river basin network that delivers water, nutrients and sediments (Brondizio et al., 2016a). Deltas are frequently densely populated as they provide multiple ecosystem services, as demonstrated by the presence of 13 of the world's 20 largest megacities in coastal/deltaic regions (Adnan and Kreibich, 2016). Deltaic social-ecological systems (SES) are dynamic systems, the highly complex characteristics of which are derived from social development and various environmental driving factors, such as sea-level rise and regional catchment management (Nicholls et al., 2016). Due to their geographical characteristics, rapid population growth and urbanization processes, and natural resources extraction, deltas are increasingly prone to elevated rates of subsidence and erosion, and are facing growing associated risk from natural hazards, especially from hydro-meteorological hazards, such as flooding, cyclones and storm surges (Syvitski et al., 2009; Tessler et al., 2015). As a consequence, coastal areas in general have suffered extensive losses both in terms of casualties and economic impacts because of natural hazards (Newton and Weichselgartner, 2014). For example, in China numerous incidences of coastal flooding between 1989 and 2014, led to over 7000 fatalities and nearly US$77 billion in economic losses alone, mainly in the Yangtze River Delta (Fang et al., 2017). As a result of such widespread impacts, risk assessments have become an important tool for assessing the potential consequences of extreme events and supporting the development of strategic measures for long-term hazard risk prevention and management. Integrated risk assessments, which apply both social and ecological perspectives, are critical to informing on development trajectories of these vulnerable landscapes (Hagenlocher et al., 2018).

1.1. Vulnerability and risk assessment frameworks

As an established method in determining how SES are threatened by natural hazards, vulnerability and risk assessments have received

Abbreviations: SES, Social-ecological systems; Delta-ES-SES, Delta-Ecosystem services-Social-ecological systems.

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increased attention in regional planning, sustainable development and global environmental management (Berrouet et al., 2018). The current methods by which we understand and address vulnerability and risk factors, as well as their apparent variability as a result of climate change, have been developed from a variety of different perspectives: hazard-centred theory (Dewan, 2013; White, 1974), political economy and political ecology (Duncan et al., 2017; McElwee et al., 2017; Wisner et al., 2004), and interdisciplinary social-ecological system interactions (Berrouet et al., 2018; Sebesvari et al., 2016). The integrative approach is conducive to observing the environmental responses and sustainability issues from the risks posed to social activities and ecological processes. To date, there is a growing trend away from risk assessments in a single social system context (or the "geography theory") and toward social and ecological coupling for delta environments (Brondizio et al., 2016b; Hagenlocher et al., 2018). Capturing this coupling is important in that it provides supporting evidence for the development of targeted adaptation measures resulting from risk analysis, especially when combined with geospatial approaches to mapping and modelling (Dewan, 2013; Frazier et al., 2014; Ogato et al., 2020; Torresan et al., 2012).

Research related to the vulnerability and risk assessments of deltas has increased in recent years, but much research has focused on considering a single hazard, especially floods (Deverel et al., 2016; Ge et al., 2017; Islam et al., 2019; Romagosa and Pons Solé, 2017; Tran et al., 2017). However, as SES are typically exposed to multiple hazards, taking a multi-hazard approach rather than a single-hazard one in assessments is essential for the development of integrated management strategies at different institutional, governmental and spatial levels. Recently, multi-hazard risk assessments for delta regions have been carried out (Hagenlocher et al., 2018; Tessler et al., 2015)).

Following the development of vulnerability and risk analysis theory, assessment models have also been developed. These mainly include the 'pressure and response model' (Kang et al., 2019; Wisner et al., 2004), the 'exposure, sensitivity and adaptability framework' (Chang et al., 2021; Sano et al., 2015) and the integrated assessment of multi-hazards method (Gallina et al., 2016). The first type of model relies on the regional level, and the second type of framework mainly focuses on a single hazard. Concerning the third type of integrated assessment framework, it combines multi-hazard perspectives with an indicator-based approach and spatial tools, which is applicable for identifying risk in detail and showing spatial relevance (Ashraful Islam et al., 2016; Hagenlocher et al., 2018; Tessler et al., 2015). Such indicator-based risk frameworks could be an effective method for assessing vulnerability and risk, especially when conducting comparative studies between large deltas (Hagenlocher et al., 2018). In fact, integrated assessments of deltaic SES are relatively rare, and the linkages between social systems and ecosystems are typically not fully considered. Current research and indicator systems mostly concentrate on social vulnerability (Cutter et al., 2003; Khajehei et al., 2020; Kirby et al., 2019; Tran et al., 2017; Vermaat and Eleveld, 2013), and social-economic factors, infrastructure assets, institutional governance and adaptations (Frick-Trzebitzky et al., 2017; Ogie et al., 2018; Sun et al., 2019; Waghwala and Agnihotri, 2019; Wood et al., 2010). Few studies have investigated ecosystem vulnerability, but most have adopted non-site-specific assessments related to ecotoxicology or are limited by the number of indicators and data quality used (De Lange et al., 2010; Sebesvari et al., 2016; Wu et al., 2018). There therefore is a need to further quantify ecosystem vulnerability and incorporate more information on ecosystems in risk assessments.

1.2. Ecosystem services studies

Since the publication of the Millennium Ecosystem Assessment (MA, 2005), there has been a notable increase in the number of studies that consider ecosystem services (Costanza and Kubiszewski, 2012). Ecosystem services are defined as the benefits that people or society derive from ecosystems, which are usually classified as supporting, provisioning, cultural, and regulating services (MA, 2005). The applications of ecosystem services-based theories use different theoretical frameworks for specific research purposes: biocentric or human-centric approaches select the applicable ecosystem service types from the classification systems for analysis and assessment (La Notte et al., 2017). Quantifying ecosystem services has become the basis of ecosystem management and decision-making processes (Braat and de Groot, 2012; Oteros-Rozas et al., 2014; Costanza et al., 2014; Wang et al., 2014; Mononen et al., 2016). Meanwhile, facing the loss and degradation of ecosystem services, there has been an increasing interest in whether ecosystem-based strategies could contribute to common benefits faced by climate change mitigation and adaptation (Tran and Brown, 2019). Considering that ecosystem services present the interaction between humans and nature, the various components of natural and social systems can be more effectively integrated by using the concept of ecosystem services. There are currently some ecosystem service frameworks for assessing vulnerability, which mainly analyse ecosystem service elements and processes that are directly related to social outcomes, for example, direct GDP outputs (Armatas et al., 2017; Berrouet et al., 2018; Mononen et al., 2016; Qiu et al., 2015; Reyers et al., 2013). However, the value of ecosystem services alone cannot fully represent the vulnerability and risk to SES, especially the physical and environmental aspects of vulnerability. In the context of sustainable development and global climate change, coupled with the fact that consideration of the ecosystem dimension was superficially addressed at best in most previously mentioned vulnerability and risk assessment approaches, this study focuses on the systematic integration of ecosystem services in order to describe coupled SES dynamics more precisely in deltas exposed to multiple hazards.

1.3. Aims

In view of the need to balance the current vulnerability domain of social and ecosystem components in the risk assessments of SES, the overarching aim of this paper was to develop a conceptual framework which combines existing vulnerability and risk assessment frameworks with ecosystem services approaches, thus building on previous methods which separated social and ecological indicators. This framework is designed to assess the vulnerability and risk to deltaic SES exposed to multiple hazards. With the proposed framework, vulnerability assessments within and across deltas can be conducted using a modular indicator-based approach, developed by integrating the role of ecosystem services. It supports methodological adjustments in various components of risk assessment framework, including (multi-)hazards perspective, a combination of geospatial techniques and spatial analysis, and indicators adjustment for national/deltaic/local scales. In order to meet these aims, we address the following objectives: 1) the adaptation of existing approaches for vulnerability and risk assessment of socio-ecological systems to allow for the inclusion of ecosystem service indicators; 2) the use of a systematic literature review to determine an appropriate list of ecosystem service indicators.

2. A proposed framework for deltas with the integration of ecosystem services

2.1. Current approaches for vulnerability and risk assessment of socio-ecological systems

One of the gaps in current vulnerability and risk assessment research is the lack of methods linking biophysical and social environments to consider the delivery of ecosystem services, especially when assessing coastal river deltas with strong social-ecological coupling (Berrouet et al., 2018; Hagenlocher et al., 2018; Olander et al., 2018; Sebesvari et al., 2016).

Based on varied emphases of SES, previous research addressed the vulnerability by proposing a number of alternative frameworks and methods: assessments for social and ecological components (Abson et al., 2012; Beroya-Eitner, 2016; Folke et al., 2005; Islam et al., 2013; Kok et al., 2016; Kumar et al., 2016; López-Angarita et al., 2014) or ecosystem services assessment (Asmus et al., 2019; de Groot et al., 2010; Pártl et al., 2017; Rissman and Gillon, 2017; Robinson et al., 2013), as presented in Fig. 1.

When assessing risks, current methods mainly structure risk drivers as well as distinguish between multiple dimensions of vulnerability (Birkmann et al., 2013). This methodology provides a conceptual basis for understanding vulnerability and risk at different spatial scales within the SES, which emphasizes the interplay between environmental changes (natural hazards) and social activities. Socio-economic activities may increase the likelihood of natural hazards, and natural hazards will in turn affect the social systems (Birkmann et al., 2013). In this approach, the hazard component usually refers to the magnitude and frequency of potentially hazardous events, which are also included in the final risk calculation (IPCC, 2014). This method is useful in that it can indicate the impact of natural hazards in either the social system or ecosystem, and can also determine the exposure and susceptibility of the overall SES. These methods consider both social and ecological aspects as separate units of analysis, using a hierarchy of indicators to identify vulnerability (Asare-Kyei et al., 2015; Bevacqua et al., 2018; Nguyen et al., 2019; Sano et al., 2015; Shah et al., 2020; Su et al., 2015). Geospatial approaches play an important role in conducting these assessments and proposing subsequent risk management, for example, the use of geographic information systems (GIS) to integrate and analyse spatial data, and remote sensing to allow hazard monitoring and mapping at various geographic or spatial scales (Dewan, 2013).

The practical disadvantages of this method are that, while some studies have integrated an SES context, they lack sufficient consideration of the ecosystems (Abson et al., 2012; Beroya-Eitner, 2016; Kok et al., 2016; Rissman and Gillon, 2017). This is largely due to the difficulty in obtaining data on ecosystem-related biophysical variables, as well as the easier availability of socioeconomic data for social vulnerability analysis, e.g. through census data. However, the interaction of social and ecosystem vulnerabilities creates overall vulnerability. Resolving problems at the social level alone, without a sufficient understanding of ecosystems and natural resources is not enough to assess and monitor the risks of SES (Folke et al., 2005). Improvements could be adding biological and ecological factors to quantify ecosystem vulnerability, such as developing the procedure to link ecosystem services to the results of ecosystem vulnerability assessments (De Lange et al., 2010).

In recognition of these issues, there has been a growing interest in the use of ecosystem services to conduct vulnerability or risk assessments at multiple spatial scales (Bevacqua et al., 2018; Asmus et al., 2019). Analysing ecosystem services as the interactions between social-economic and biophysical factors could enable greater understanding of SES from the aspects of ecosystem services, human activities and the biological environment (Collins et al., 2011). Additionally, combining vulnerability assessment with the qualitative assessment method of ecosystem services could promote the most suitable management steps to prevent ecosystem services loss and degradation (Bouahim et al., 2015). In general, ecosystem services have two main roles in vulnerability and risk assessments: quantifying ecosystem services to represent vulnerability (Lilai et al., 2016; Silver et al., 2019), or emphasizing the importance of ecosystem services to provide guidance when developing environmental management policies (Khan et al., 2019; Lozoya et al., 2015). Existing classifications of ecosystem services such as the Millennium Ecosystem Assessment (MA), the Economics of Ecosystems and Biodiversity (TEEB) and the Common International Classification of Ecosystem Services (CICES) provide robust frameworks for identifying and measuring ecosystem services (Haines-Young and Potschin, 2018a; Ma, 2005; Sukhdev and Kumar, 2008). Ecosystem services analysis currently uses proxy variables to show ecological processes and mostly involves stakeholder engagement in evaluating indicators and management opinions; the results of this qualitative analysis and the practical use of arbitrary categorical indicators create uncertainty in the results (Seppelt et al., 2011). Ecosystem services mapping has also developed in recent years, combining various spatial data to map ecosystem service flow to social systems in different scales (Affek et al., 2020). This standardization has been widely applied in the research of ecosystem services, providing scientific guidance for sustainable management of natural resources.

Both previous risk assessment frameworks and emerging ecosystem service classification frameworks adopt indicator-based assessment methods in practice, which is conducive to building an integrated conceptual approach. The combination of quantitative and qualitative methods also provides a broader perspective by which to interpret the

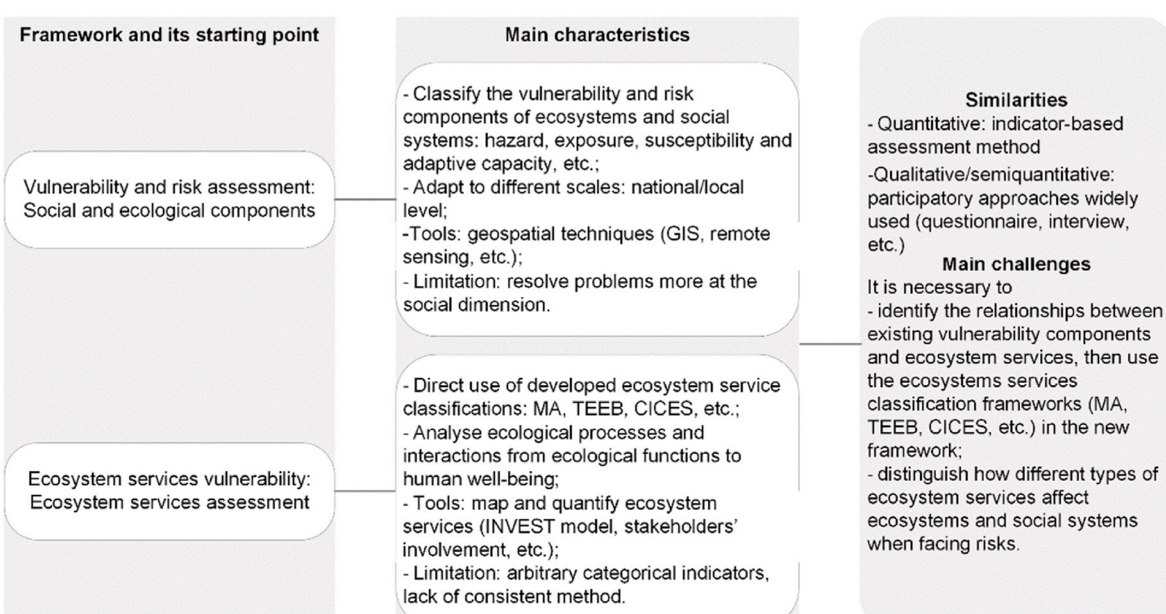

Fig. 1. Assessment methods, main characteristics and challenges for vulnerability and risk analysis.

relevance and feasibility of the results of the analysis. In view of this, ecosystem service indicators can be used to supplement social vulnerability indicators and ecosystem vulnerability indicators, thereby enabling improved vulnerability and risk assessment of the deltaic SES and being more relevant in terms of recommendations for policy-makers and decision-makers. To be effective in this regard, three issues need to be addressed. Firstly, the need to comprehensively identify the relationships between ecosystem services and other vulnerability components in the risk framework. This will directly affect at which level the ecosystem service classification is placed in the vulnerability framework. Secondly, the need to understand the biophysical processes or ecological mechanisms underpinning different ecosystem services, and thirdly, to determine the dependence of social systems on those different types of ecosystem services.

2.2. Proposed vulnerability and risk framework incorporating the role of ecosystem services

The proposed framework is adapted from the Delta-SES framework published by Sebesvari et al. (2016), as it is relatively comprehensive due to its SES perspective and effective combination of the social and ecological dimensions of vulnerability, while also capturing the multiple hazards faced by SES at different spatial scales. This framework has been used by Hagenlocher et al. (2018) to assess risks in the Mekong, Ganges-Brahmaputra-Meghna and Amazon deltas and by Anderson et al. (2021) for the Mississippi delta. The main difference between the proposed Delta-ES-SES framework (Fig. 2) and the pre-existing Delta-SES framework is the inclusion of ecosystem services in the vulnerability component. In addition, we have reverted to a more classical and explicit representation of risk by considering the hazard components such as magnitude, severity, duration and probability of occurrence (IPCC, 2014; Shah et al., 2020). Risk will be calculated as Hazard × Exposure × Vulnerability (IPCC, 2014). In the process of vulnerability analysis and assessment, the ecosystem, ecosystem services and social system are divided into separated components, as shown in Fig. 2.

The proposed Delta-ES-SES framework considers that vulnerability is related to (1) ecosystem services with cross-scale ecological and social processes, (2) social vulnerability, and (3) ecosystem vulnerability. Among these, ecosystem vulnerability is composed of ecosystem susceptibility, ecosystem robustness, and social vulnerability is composed of social susceptibility, coping capacity, and adaptive capacity (Sebesvari et al., 2016). Within this framework, ecosystem service indicators serve as an intermediary that relates the biophysical and social environments and either replace or integrate appropriate vulnerability indicators of both sub-systems. For example, soil organic matter is widely used to represent soil quality and habitat degradation (Hagenlocher et al., 2018), which is considered a key attribute in providing energy and substrates to sustain soil functions (Franzluebbers, 2002). From the final service provided by soil quality regulation, indicators like nitrogen fixation rate and nutrient cycling index can be regarded as the ability of plant roots to absorb nutrients, and better represent the impact of hazards on crop production and social benefits. The selection and treatment of individual ecosystem service indicators selection are explained below. Then, a number of ecosystem services not analysed in previous studies will be used to supplement the vulnerability domain, increasing the dimension of ecosystem context within the framework. As some ecosystem vulnerability indicators have considered ecosystem services, they will also be incorporated into the list of ecosystem service indicators (such as water quality) (Hagenlocher et al., 2018).

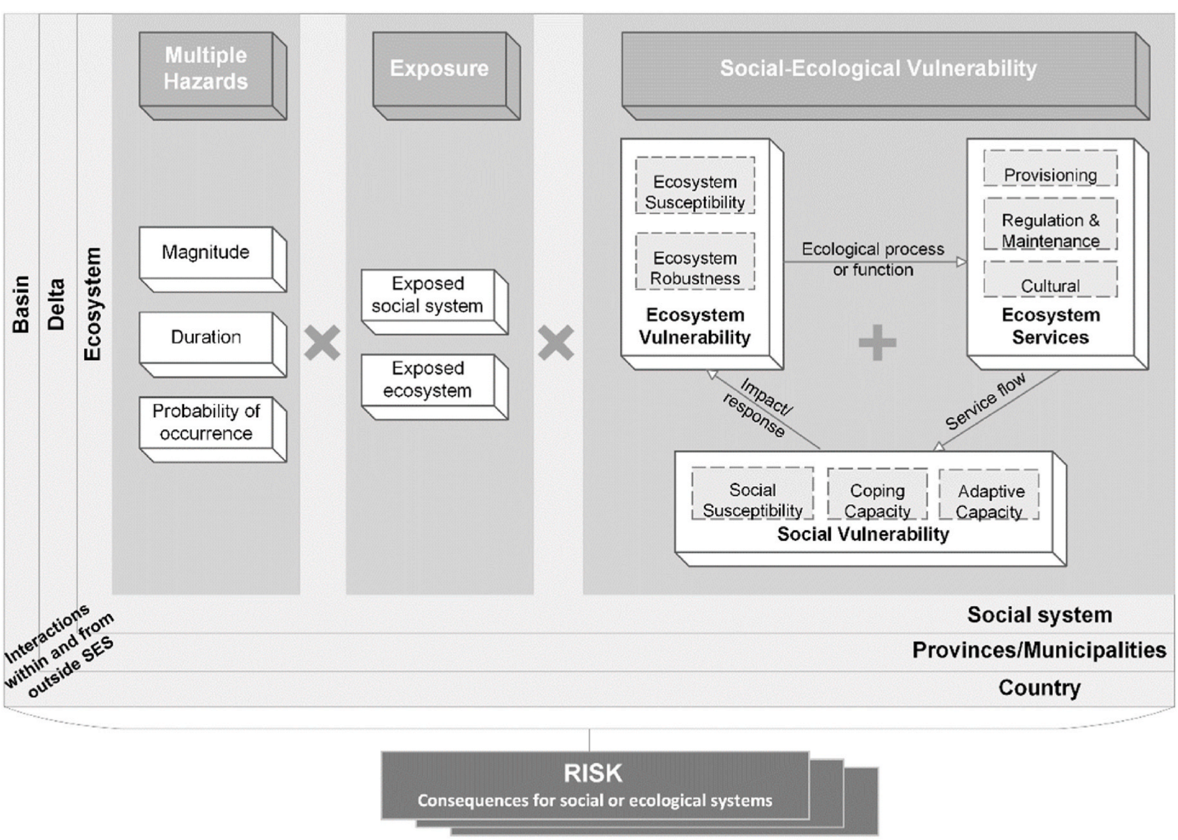

Fig. 2. Conceptual framework for vulnerability and risk assessment of SES in deltas (Delta-ES-SES). Modified from Sebesvari et al. (2016) and IPCC (2014); Shah et al. (2020).

3. Ecosystem services in relation to vulnerability and risk assessments

3.1. *Identifying ecosystem services relevant to risk assessments in deltaic and coastal areas*

The Common International Classification of Ecosystem Services (CICES) developed by the European Environment Agency is used to provide a systematic and scientific classification of ecosystem services with detailed division, group, class and corresponding example services (Haines-Young and Potschin, 2018a). Within this system, ecosystem services are divided into (1) provisioning services, such as biomass, energy and water provision; (2) regulating & maintenance services, such as soil quality regulation; and (3) cultural services, such as recreation. This classification system was selected for two reasons. First, it seeks to classify the final ecosystem services, which are closely related to the corresponding ecological process and directly affect human well-being (Haines-Young and Potschin, 2018b). Changes in the apparent or output scale of ecosystem services can be considered as a response to ecosystem susceptibility and also affect ecosystem robustness and social susceptibility. This is useful for drawing interlinkages between ecosystems and social systems in vulnerability and risk assessments. Secondly, CICES not only provides detailed definitions for various classes of ecosystem services but also lists the corresponding roles of each indicator in other ecosystem classifications, such as MA and TEEB. Therefore, when analysing and summarizing the ecosystem service indicators, it can provide comparison and guidance, and then organize them into a unified classification. As a result of these benefits, it has been widely used as a scientific classification tool in research related to ecosystem services (Czúcz et al., 2018; Maes et al., 2016).

The addition of ecosystem services to risk assessment includes the following steps. Firstly, different types of ecosystems are identified for the delta context. Deltaic environments may be divided into either aquatic ecosystems and terrestrial ecosystems (Sebesvari et al., 2016). According to the studies on ecosystem services in deltas, various ecosystem services in the terrestrial and aquatic ecosystems are considered separately. Then, in order to identify the application of various ecosystem services in similar studies, a systematic review of published literature on vulnerability or risk assessments for deltaic or coastal environments that integrate the perspective of ecosystem services was conducted using Scopus. We choose SCOPUS as it is better suited for both evaluating research results and for performing daily tasks, particularly as Scopus is subscribed as a single database, without confusion or additional restrictions regarding content accessibility (Pranckutė, 2021). The main purpose of this step was to determine what categories of ecosystem services are provided by different ecosystem types and could be considered in vulnerability analysis. This review followed the ROSES flow diagram for systematic reviews (Haddaway et al., 2017). The search terms and screening process are shown in Table 1.

In total, 1637 articles were returned, which were filtered down to 57 after title, keywords, and abstract review. These 57 articles were subject to a full-text read-through to check whether ecosystem services were a central consideration. Articles not related to vulnerability or risk assessments or that did not incorporate ecosystem services into the actual research were excluded. In the end, the study reviewed 17 papers (Fig. 3). The data shows that there are relatively few studies ($n = 8$) that quantify ecosystem services when conducting vulnerability and/or risk assessments in deltas or coastal areas. Based on the ecosystem services noted in the literature review and CICES, we recorded ecosystem service divisions and indicators that can be used for constructing a risk index. In addition to mapping the ecosystem services to CICES, we also combine the practical studies in the CICES V5.1 Guidance to provide example indicators for each ecosystem service division, and then incorporated them into the vulnerability and risk analysis.

Based on the analysis of the literature, the final set of 17 CICES groups and 55 ecosystem service indicators were extracted following the CICES V5.1 Guidance papers (Supplementary Material 1). Table 2 shows the most important ecosystem services reported in reviewed papers, which reflects the primary ecosystem services considered in different ecosystem types. Generally, the main ecosystem service divisions are all considered, but different studies have different focuses, which is specifically reflected in the choice of ecosystem service indicators. Distinguishing the closely related ecosystem services for different types of ecosystems can allow determining which ecosystem services need to be considered when addressing risks in a chosen environment.

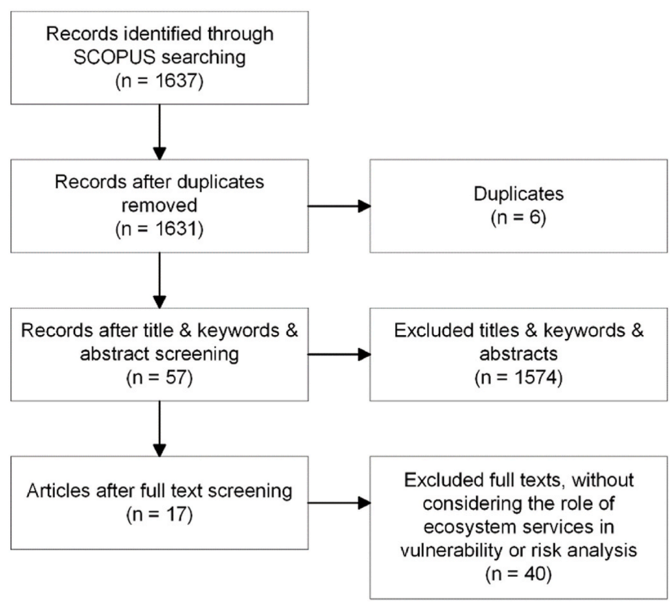

Fig. 3. Summary diagram indicating the outputs of screening and exclusion processes of the recovered body of literature.

Table 1
Search terms used in the review.

Risk components		Assessment elements		Ecosystem		Landscape
Risk **or** Vulnerability **or** Hazard	**AND**	Framework **or** Model **or** Indicator **or** Assessment	**AND**	Ecosystem **or** Service	**AND**	Delta **or** Coast
Search string	TITLE-ABS-KEY ((risk OR vulnerability OR hazard) AND (framework OR model OR indicator OR assessment) AND (ecosystem OR service) AND (delta OR coast)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “AGRI”) OR LIMIT-TO (SUBJAREA, “EART”) OR LIMIT-TO (SUBJAREA, “SOCI”) OR LIMIT-TO (SUBJAREA, “MULT”) OR LIMIT-TO (SUBJAREA, “DECI”)) AND (LIMIT-TO (PUBSTAGE, “final”)) AND (1978’ has/have not been found in the reference list. Please add the corresponding reference(s) to the reference list.>PUBYEAR > 1978))					

Table 2
An overview of the main ecosystem services for different ecosystems.

CICES Division	Ecosystem types			
	Aquatic ecosystem	Aquaculture ecosystem	Terrestrial ecosystem	Agroecosystem
Provisioning				
Biomass: food	✓	✓	✓	✓
Biomass: raw materials	✓	✓		
Energy	✓		✓	✓
Water for drinking	✓	✓	✓	✓
Water for non-drinking purposes	✓	✓		
Regulation & Maintenance				
Water regulation	✓	✓	✓	✓
Erosion regulation	✓	✓	✓	✓
Habitat protection	✓		✓	✓
Biodiversity	✓	✓		
Pollination			✓	✓
Air quality regulation	✓	✓	✓	✓
Soil quality regulation	✓	✓	✓	✓
Climate regulation	✓	✓	✓	✓
Natural hazard protection			✓	✓
Cultural				
Recreation	✓	✓	✓	✓
Natural and cultural Heritage	✓	✓	✓	✓
Aesthetic	✓	✓	✓	✓

3.2. *Incorporating ecosystem services into vulnerability domains*

The indicator selection procedure mainly follows a deductive approach, which includes drawing interlinkages from the proposed framework and selecting ecosystem service indicators based on the relationships and processes (Adger et al., 2005). The first step includes outlining the main processes or relationships between ecosystems, ecosystem services and human well-being. The second step is to link and contextualize these processes and draw the relevance among ecosystem vulnerability, ecosystem services and social vulnerability. The last step consists of selecting possible ecosystem service indicators to construct the final indicator list. Each group of ecosystem services can be represented by many indicators, and the specific application depends on the research focus; Additionally, some ecosystem services are difficult to measure directly, so proxy ecosystem services indicators are needed to conduct a meaningful assessment (Seppelt et al., 2011). The interactions and processes of the deltaic SES are mainly considered in accordance with the SES vulnerability cascade model adapted from de Groot et al. (2010) (Fig. 4). This model can be further operationalised by linking the ecological processes that affect various ecosystem services and the resulting impacts on the social system (MA, 2005).

The application of the SES vulnerability cascade framework to establish the links between ecosystem services, ecosystem vulnerability and social vulnerability is presented in Fig. 5. Using the example of the soil quality regulation service we follow a deductive approach to establish relationships between vulnerability components proposed by the Delta-ES-SES framework. An ecosystem produces a variety of ecosystem services, and they interact with each other in a complex relationship, for example, soil quality is closely related to erosion regulation and biodiversity (Braat and de Groot, 2012). This study is based on the starting point of vulnerability assessments, and mainly considers its relationship between ecosystem services and habitats and humans separately.

As illustrated in the example, a terrestrial ecosystem provides the biophysical environment for soil quality regulation service. Soil may provide nutrients to plants via nutrient cycling, biological nitrogen fixation and weathering (Schröder et al., 2016). Of these, the ecological process related to soil quality regulation is nutrient cycling, which includes the recovery and reuse of nutrients in soil organic residues (Schröder et al., 2016). The cycling of these nutrients (such as nitrogen and phosphorus) and filtering and buffering of organic compounds, heavy metals and contaminants are the main ecological functions provided by soil (Drobnik et al., 2018). Soil microorganisms convert inaccessible forms of nitrogen into useable forms, a process known as soil nitrogen mineralization (Li et al., 2014). Soil quality represents its ability to absorb nutrients and convert them into components that can be used by plants, thereby affecting the productivity of crops. Generally, there is a positive correlation between soil organisms, degree of mineralization and crop yield (Schröder et al., 2016).

Current vulnerability research considers habitat degradation, which includes indicators that take into account soil organic matter (Hagenlocher et al., 2018). However, the levels of soil organic matter do not represent the recovery and reuse of mineralized nutrients, nor do they take into account actual uptake or deficient levels of plant communities. Compared with an ecosystem vulnerability indicator (soil organic matter), indicators related to N content (such as mineralization rate, legume nitrogen fixation rate, etc.) enable assessment of the nutrient cycle and the ability to maintain soil quality. When quantifying existing or altered

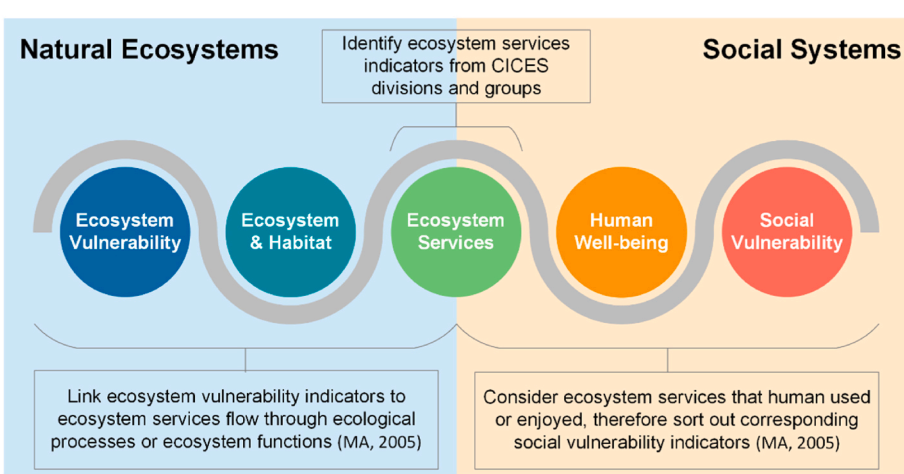

Fig. 4. SES vulnerability cascade model modified from (de Groot et al., 2010).

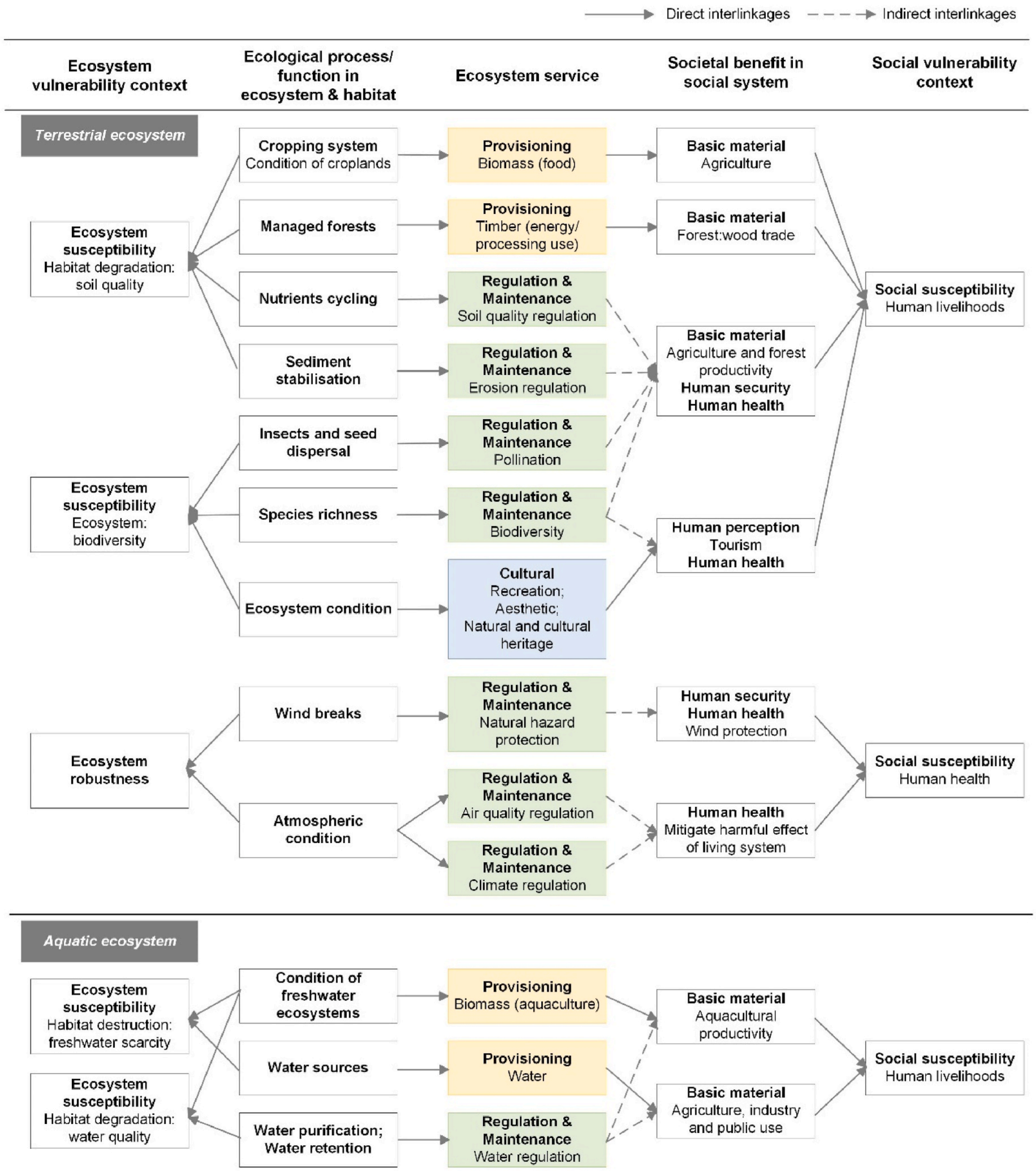

Fig. 5. Schematic overview of the main interlinkages between ecosystem vulnerability, ecosystem services and social vulnerability. Among them, provisioning services, regulation & maintenance services and cultural services are represented by yellow, green and blue boxes, respectively. The arrows with solid line mean a direct relationship. The arrows with dash line show indirect linkages (Regulation & Maintenance services). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

soil quality regulation, considering nitrogen fixation rate or gross nitrogen balance could integrate ecological functions with how many services can be used/provided. Obviously, the use of ecosystem service indicators can take into account ecological functions and their availability, and they are also closely related to social benefits and human activities (such as biomass production). Similar to the analysis process of soil quality regulation, Supplementary Material 2 provides the detailed description and a full list of the selected ecosystem services indicators.

From the context of vulnerability assessment, the enhanced development and use of ecosystem services reflect the possible impact of complex coupling processes on the ecosystem and social systems. After a more complete assessment of vulnerability and risk, strategies related to improving coping and adaptive capacity and risks reduction can also be more accurately determined. When assessing the selected deltas, an inductive approach can be combined to further select the final set of indicators, such as through expert consultation and stakeholder workshops.

4. List of indicators for vulnerability and risk assessments

Building on the work of Hagenlocher et al. (2018) and using the ecosystem service list generated during our literature review (Supplementary Material 1), 145 indicators related to risk are proposed. Of these, 22 indicators are related to hazards and SES exposure. After identifying the ecosystem service indicators, all other vulnerability indicators were listed according to the three main components of the proposed Delta-ES-SES framework. This resulted in 32 ecosystem service indicators. The social vulnerability (59) and ecosystem vulnerability (32) indicators were identified from published articles in the context of deltas. Overall, the proportions of indicators of ecosystem vulnerability, ecosystem services and social vulnerability represent 26%, 26% and 48% of all indicators, respectively. 64 indicators (52%) are related to ecosystem context, thereby giving increased prominence to ecosystem-related indicators when compared to previous risk assessment approaches. Supplementary Material 3 provides an overview of the final list of indicators for each component that can be used to support future studies. The following sections provide detailed information for different components in the Delta-ES-SES framework.

4.1. Ecosystem services indicators related to vulnerability

Ecosystem service indicators are divided into provisioning, regulation & maintenance and cultural services, covering both of terrestrial and aquatic ecosystems in deltas. Table 3 provides examples of selected ecosystem service indicators of vulnerability that can be used to support future studies. Selected ecosystem services are also mapped to different vulnerability components. Some ecosystem vulnerability indicators (such as biodiversity) now belong to the regulation and maintenance services of the ecosystem services component. Additionally, some social vulnerability indicators (such as dependency on agriculture for livelihood) have been chosen to reflect the ability of provisioning services by ecosystems. These vulnerability indicators are classified as ecosystem service indicators in the new framework.

In terms of provisioning services, indicators such as crop production by terrestrial ecosystems, aquaculture production and water supply by aquatic ecosystems pertain to the ecosystem's ability to provide nutrition, materials or energy (Haines-Young and Potschin, 2018b). Generally, provisioning services indicators are easier to obtain, such as harvested production volumes and other similar indicators. Regulation and maintenance services include converting biochemical or physical inputs into ecosystems, and then regulating people's biophysical and chemical environments in a beneficial way (Haines-Young and Potschin, 2018b). The regulation and maintenance services in turn affect the supply of provisioning services. For example, soil quality regulation services indirectly affect the social system through provisioning services such as agricultural productivity, which in turn affects social benefits and human activities. Regulation and maintenance services mainly include soil quality regulation (nutrient recycling, nitrogen fixation rate), erosion regulation (soil retention), pollination, biodiversity (species richness), natural hazard protection (percentage of windbreaks area), air quality regulation (removal of NO_2), climate regulation and water regulation (water quality, groundwater quality and water retention index). Cultural services consider the natural settings and the interaction between cultural landscapes and living systems. The specific manifestation of cultural services depends on the living process of humans, such as the development of tourism (e.g. percentage contribution of tourism to GDP). All these indicators are based on the perspective of ecosystem services and can characterize the vulnerability of ecosystems, living systems and social systems.

Table 3
Examples of ecosystem service indicators related to vulnerability identified from Fig. 5 (see Supplementary Material 2 for the detailed information and indicator selection procedures). The full indicator list and corresponding references are provided in Supplementary Material 3.

Ecosystem service division	Indicator name/Unit
Provisioning	
Agriculture	Volumes of harvested production/ton year^{-1} per capita
Forestry	Harvested production of energy crops/ton year^{-1} per capita
Water resource	Total groundwater recharge/mm year^{-1}
Aquaculture	The amounts of aquaculture production/ton year^{-1} per capita
Regulation & Maintenance	
Soil quality regulation	Aggregated index of nutrient recycling potential/index
	Nitrogen fixation rate/kg ha^{-1}year^{-1}
	Soil retention/ton ha^{-1}year^{-1}
Pollination	Pollination potential/index
Biodiversity	Biodiversity Intactness Index/index
Natural hazard protection	Percentage of protected area/%
Air quality regulation	Removal of NO_2 by urban vegetation/ton ha^{-1} year^{-1}
Water regulation	Water quality/index
	Water Retention Index/index
Cultural	
Tourism	Aggregated index generated through recreation and tourism statistics/index
	Percentage of tourism to GDP/%

4.2. Indicators related to ecosystem exposure and ecosystem vulnerability components

Deltas encompass ecosystems with different characteristics (terrestrial, aquatic, coastal, etc.). The indicators related to ecosystem exposure are the proportions affected by different natural hazards (e.g. floods), as shown in Table 4. The ecosystem susceptibility to natural hazards shows the degree to which the ecosystems are adversely affected by climate change (IPCC, 2022), which is related to the state of habitats and ecosystems. Aspects related to ecosystem biodiversity have been considered in the ecosystem service section. Here, ecosystem susceptibility indicators are mainly divided into three categories: habitat destruction, habitat degradation and habitat fragmentation. Some factors related to soil quality help determine the condition of the habitat status, for example, vegetation loss and the use of chemicals and fertilisers can determine the extent of destruction and degradation, respectively (see Supplementary Material 3 for the final indicator set). Additionally, according to Hagenlocher et al. (2018), indicators such as forest connectivity can represent the level of habitat fragmentation in different ecosystems.

Ecosystem robustness represents the capacity of ecosystems to stabilize various ecological functions and reduce risks (Sebesvari et al., 2016). Previous studies have listed a series of indicators related to the ecological environment and relevant environmental policies to assess the ecosystem robustness, such as the percentage of government expenditure on environmental protection (Hagenlocher et al., 2018).

Table 4
Example indicators related to exposed ecosystems and ecosystem vulnerability identified from the literature review (see Supplementary Material 3 for the full list and references).

Risk components	Indicator name/Unit
Ecosystem Exposure	
Exposed ecosystem	Ecosystem exposed to flooding/%
Ecosystem Susceptibility	
Habitat destruction	Percentage of vegetation loss/%
Habitat degradation	Increased use of chemicals and fertilisers (qualitative/ quantitative)
Habitat fragmentation	Forest connectivity/index
Ecosystem Robustness	
Ecosystem & Habitat	Ecosystem Functionality Index/index
Ecosystem conservation	Policies supporting biodiversity conservation (yes/no)
	Percentage of government expenditure on environmental protection/%
Ecosystem restoration	Percentage of nature reserves and wetlands/%

4.3. Indicators related to social system exposure and social vulnerability components

Various indicators related to the exposure of the social system and social vulnerability were identified in the reviewed papers (Table 5). A full list of indicators is provided in Supplementary Material 3. When combined, these indicators summarise the characteristics of the exposed population while also considering economic exposure, and the exposure of houses (buildings) and infrastructure, which together constitute social system exposure (Shah et al., 2020). Previous research has identified a variety of social susceptibility indicators, dividing them into the three main categories of key services, human livelihoods and human health. The key services consider various factors and infrastructure providing basic services and other elements of well-being, such as the percentage of the population without access to electricity (Hagenlocher et al., 2018). Human livelihood includes a series of indicators related to social, economic and demographic characteristics, such as the percentage of primary industry to GDP and percentage of illiterate population.

Coping capacity is mainly divided into two components: individuals and households; and infrastructure and services. These outline the ability of individuals and social systems to address, manage and overcome hazards and risks (IPCC, 2022), such as the percentage of population without a health insurance and existence of early warning. Adaptive capacity refers to the apparent scope to reduce adverse impacts and risks, which is assessed from the social perspective and government management. It includes two aspects: social adaptation (e.g. density of aid projects) and institutional adaptation (e.g. existence of hazard/vulnerability/risk maps).

5. Discussion and outlook

Ecosystem services have developed into a paradigm of ecosystem management, with concepts that combine biophysical, economic, and institutional management perspectives (Seppelt et al., 2011), relevant to the theoretical underpinnings of vulnerability and risk analysis. By considering ecosystem services, this paper advances the methodological framework that can be used to analyse the vulnerability and risk to deltaic SES exposed to multiple natural hazards. It proposes an SES vulnerability cascade model to develop vulnerability indicators related to ecosystem services from biophysical processes or ecological functions and social contexts. By combining the role of ecosystem services, the Delta-ES-SES framework has the potential to improve risk assessment of deltaic SES. In addition, we put forward a standard list of interconnected indicators to address risk in all dimensions of physical, environmental, economic, and livelihoods, as related to natural hazards (e.g. drought, floods, cyclones, storm surge) that have a greater probability of occurrence in deltas. This Delta-ES-SES framework and the preliminary indicator library are not developed for specific deltas but represent the main indicators that can be suitable for most delta environments. Pre-defined list of indicators covering various dimensions has become an integral method of risk mapping and visualization, which could express the risks of natural hazards across various geographic and spatial scales of SES (Gallina et al., 2016). Additional indicators need to be further identified and developed both generally and for specific delta contexts.

Table 5
Example indicators related to exposed social system and social vulnerability identified from the literature review (see Supplementary Material 3 for the full list and references).

Risk components	Indicator name/Unit
Social System Exposure	
Exposed population	Percentage of population exposed to flooding/%
Exposed economy	Proportion of GDP in primary sector/%
Exposed houses	Proportion of houses with poor facilities that are more fragile to climate change and hazards/%
Exposed infrastructure	Proportion of critical transportation sector/%
Social Susceptibility	
Key services	Percentage of population without access to electricity/%
	Percentage of population living in poorly-constructed houses/%
Human livelihoods	Percentage of illiterate population/%
	Percentage of primary industry to GDP/%
Coping Capacity	
Individual and household	Per capita income
	Percentage of population without a health insurance/%
Infrastructure and services	Existence of early warning systems (yes/no)
	Volume of water storage in a safe reservoir/container/m^3
	Number of hospital beds per 1000 inhabitants
Adaptive Capacity	
Social adaption	Density of aid projects/index
Institutional adaption	Existence of hazard/vulnerability/risk maps (yes/no)
	Existence of integrated development plans: conservation, protection; land use planning (yes/no)

As described, the Delta-ES-SES framework divides multi-hazard risk assessment into multi-layer modules, which support integration with a wide range of existing methods. As an essential tool, GIS provides a facilitated visualization of risk distribution, making the risk profile of the entire study area easy to observe and analyse (Dewan, 2013). Meanwhile, being able to perform a single analysis of each component can also help to identify specific risk drivers, which can lead to more targeted strategies for risk reduction measures (Hagenlocher et al., 2018). Remote sensing and hydrological models can play an important role in hazard identification and data collection, especially in areas where data is lacking (Dewan, 2013). To localize data and knowledge, increased involvement of experts in defining priorities of indicators and stakeholders' perceptions can also provide a more specific, local, and targeted path to analysis (Gallina et al., 2016).

The biggest challenge in carrying out a risk assessment using this framework and the proposed indicator library is the underlying data for the indicators and data availability at the relevant spatial scale. This is also true of existing models (Kappes et al., 2012). Indeed, the data reliability of the indicators, especially the selection of ecosystem service indicators is a point worthy of attention. On the one hand, the quantification of ecosystem services requires consideration of scale and resolution (de Groot et al., 2010), which may be difficult to obtain within the constraints of a research project. On the other hand, the selection of ecosystem service indicators needs to address specific research goals. In other words, each division of ecosystem service contains many characteristics, so it is necessary to further select indicators based on the assessment focus and research area, or try to develop some integrated or composed indicators to quantify ecosystem services as comprehensively as possible. In addition, most listed indicators are derived from the risk assessment practice at a local scale. If applied in other regions, it may be difficult to find data for the indicators. As a complex SES, deltas often cover different ecosystems and administrative units. Indicator-based spatial analysis has its limitation, making it difficult to maintain updated data availability across the entire study area, especially for large basins or deltas. The administrative units can often be regarded as the basic unit of data collection, this may influence the accuracy of sub-delta risk assessment to a certain extent. For a more accurate representation of vulnerability and risk, close collaboration should be made with local communities, and governments. Collaborative research across multi-stakeholders, multi-technologies, multi-disciplines and multi-scales also further promotes risk management and policy development in a scientific and sustainable way.

The Delta-ES-SES framework builds on existing frameworks and aims to improve vulnerability and risk assessments by incorporating ecosystem services indicators to link social and ecological systems more dynamically. It therefore allows a better characterization of social-ecological systems and hopefully their vulnerability and risk to natural hazards.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116682.

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