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Incorporating ecosystem services in a multi-hazard risk assessment framework to inform disaster risk reduction and climate change adaptation in coastal river deltas

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Abstract

Coastal river deltas face increased exposure, vulnerability and risks linked to multiple natural hazards, stemming from the interplay of often linked factors such as higher population densities, rapid urbanization, low-lying topography, land subsidence and global climate change impacts. Enhancing our ability to respond to the impacts of climate change, while promoting strategies for risk reduction and adaptation, have garnered global attention. Essential to this effort are vulnerability and risk assessments, critical for mapping, managing and reducing risks and concurrently contributing to sustainable development.

In-depth exploration of climate change impacts in deltaic landscapes and of the theoretical and methodological evolution in assessing vulnerability and risks has highlighted the evolving landscape of risk assessment methodologies, including shifts (1) to consider socio-ecological systems as starting points of analyses, (2) from single to multi-hazard risk assessments, and (3) considering the role of ecosystem services to address climate change adaptation and risk reduction concerns. Current vulnerability and risk assessments focus primarily on social aspects, and often neglect the balanced incorporation of a socio-ecological systems perspective, potentially resulting in incomplete assessments. Hence, addressing this scientific gap in this research involves incorporating the role of ecosystem services into vulnerability and risk assessments, emphasizing the overall principle of ecosystem services as a bridge connecting socioeconomic and biophysical systems.

Building on existing vulnerability and risk assessment frameworks, a revised indicator-based framework for deltaic social-ecological systems is proposed in addition to a list of ecosystem service indicators identified via literature review. Ecosystem service indicators, which capture the intricate interactions between human society and natural environments, can be used to better characterize the mutual dependencies between social and ecosystem vulnerability. This enhanced framework stands as an effective tool to determine the vulnerability and risk of coastal deltas, facilitating the assessment of multi-hazard risks within and across deltas, and allowing targeted ecosystem-based adaptation measures and policies.

In conjunction with the development of a comprehensive risk assessment framework, this study implements the approach alongside a modular indicator library in capturing the muti-hazard risk characteristics of all cities in the Pearl River Delta (PRD) and the Yangtze River Delta (YRD) regions in China. For each region, expert consultations were conducted to enhance the understanding of the study sites and determine the final indicator list and their weighting assignments. Comparative analyses show a higher risk level in the PRD, predominantly concentrated along its coastal zones. Even though risk levels may appear similar, key drivers of risk sub-components vary at different spatial scales. Ecosystem services have been identified as important factors explaining the risk profiles of the deltas' cities, underscoring the importance of their inclusion into strategies aimed at disaster risk reduction and climate change adaptation.

The research further compares two risk assessment frameworks that comprehensively incorporate both social and ecological dimensions in order to analyse differences in regional vulnerability and risk levels caused by different risk components within the deltas. The newly proposed framework enables the identification of key ecosystem services and priority regions related to disaster risk and establishes their linkages with existing ecosystem-based adaptation (EbA) practices and global/national policies, thus promoting EbA success in vulnerable regions exposed to natural hazards.

This study used a mixed quantitative and qualitative approach to map the risk distribution in two large deltas, aiming to visualize hazard-prone and highly vulnerable areas and differentiate priority regions for EbA implementation. Different weighting assignment methods and assessment frameworks are compared in practice to reduce results uncertainty. The proposed risk assessment framework allowed clarifying (multi-)hazard risk components and can be easily adjusted from the delta scale down to the regional/community scale. Future development of down-scale and ecosystem-specific EbA initiatives requires more accurate and locally relevant data. In this context, future research calls on the academic and all levels of government to address data scarcity, improve cross-disciplinary knowledge integration, and enhance the participation of local sectors and communities.

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Yuting Peng

January 2024, Dumfries

Author’s Declaration

I declare that, except where explicit reference is made to the contribution of others (e.g. public datasets), this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

The chapter 2, 3, and 4 in this thesis are presented as an ‘Alternative Format Thesis’. The guideline of ‘Alternative Format Thesis’ derived from the University Code of Practice has been followed. Hence the texts, figures, and tables presented in Chapter 2, 3, and 4 are largely identical to the published or submitted versions, with additional details incorporated as requested by the thesis examiners. The serial numbers and format of tables, figures, appendices, and references have been adjusted to ensure consistency throughout the entire thesis text. Supplementary materials from those papers (e.g. data sources) have been moved into the Appendices section of the thesis.

Yuting Peng

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List of Acronyms and Abbreviations

AHP	Analytic Hierarchy Process
CBD	Convention on Biological Diversity
CCA	Climate Change Adaptation
CICES	Common International Classification of Ecosystem Services
CRED	Centre for Research on the Epidemiology of Disasters
Delta-ES-SES	Delta-Ecosystem service-Social-ecological system
DRR	Disaster Risk Reduction
EbA	Ecosystem-based Adaptation
Eco-DRR	Ecosystem-based Disaster Disk Reduction
EM-DAT	Emergency Events Database
ES	Ecosystem Services
GBF	Kunming-Montreal Global Biodiversity Framework
GBM	Ganges-Brahmaputra-Meghna
GDP	Gross Domestic Product
GDRI	Global Delta Risk Index
GIS	Geographic Information Systems
IAHP	Improved Analytic Hierarchy Process
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
LULC	Land Use / Land Cover
MA	Millennium Ecosystem Assessment
MOVE	Methods for the Improvement of Vulnerability Assessment in Europe
NBS	Nature-based Solutions
OECD	Organisation for Economic Co-operation and Development
PRD	Pearl River Delta
SDGs	Sustainable Development Goals
SES	Social-ecological system
SFDRR	Sendai Framework for Disaster Risk Reduction
SPEI	Standardized Precipitation Evapotranspiration Index
SSP	Shared Socioeconomic Pathway
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction

UNFCCC	United Nations Framework Convention on Climate Change
YRD	Yangtze River Delta

1. Introduction

According to a World Bank's report (Agwe et al., 2005), a global area of approximately 3.8 million km^2, home to around 790 million people, is highly exposed to multiple natural hazards, in which 0.5 million km^2 with 105 million people are exposed to three or more hazards. Over the last decade, natural hazard-related disasters have resulted in an average annual death toll of 45,000 people globally (Ritchie and Rosado, 2022). Many studies indicate that climate change may increase the frequency and severity of some natural hazards (Risser and Wehner, 2017; Strauss et al., 2021; Winsemius et al., 2016), suggesting that this current exposure will increase in coming decades. Disasters from natural hazards led to economic losses of US$223.8 billion in 2022, exceeding the average annual loss of US$187.7 billion from 2002 to 2016 (CRED, 2023a). The 387 cases of natural hazards-related disasters recorded in 2022 alone affected 185 million people, resulted in the loss of more than 30,000 lives (CRED, 2023a). Most prominently, driven by conducive conditions for agriculture, trade and other economic activities, nearly one billion people presently reside in floodplains (Di Baldassarre et al., 2013). Even with enhanced coping capacities in recent years, there is evidence of a rising trend in the number of deaths from flooding, with the average per year increasing from 5,066 (2010-2019) to 5,886 deaths (2020-2023) (CRED, 2023b).

Deltas are recognized as critical global risk landscapes due to high exposure and vulnerability of people, assets, and ecosystems in these areas to various natural hazards (IPCC, 2022a). For example, over 40% of the global population affected by flooding from tropical cyclones resides in deltas (Edmonds et al., 2020). These landscapes face heightened risks stemming from climatic risk drivers and changes in socioeconomic conditions, such as population growth, infrastructure and asset increases (Oppenheimer et al., 2019). The Pearl River and the Yangtze River deltas in China, the most and third most urbanized river delta regions globally, respectively, exhibit high population density, economic development, and significant exposure to various natural hazards (Scown et al., 2023). The demographic and economic significance of the deltas underscores the critical importance of managing and reducing the risks faced by the region to reduce hazard impacts and achieve sustainable development.

Several policies and agreements, notably the Paris Agreement and the Sendai Framework for Disaster Risk Reduction (SFDRR) in 2015 (UNFCCC, 2015; UNDRR, 2015), play a critical role in enhancing risk reduction from natural hazards while also aligning with the sustainable development goals (SDGs) outlined in the 2030 Agenda for Sustainable Development (UN, 2015) and implementation plan for the New Urban Agenda (UN, 2016). In this context, vulnerability and risk assessment have evolved to consider coupled social-ecological systems to capture all dimensions of exposure, vulnerability, hazard and natural environment. This approach aligns with Priority 1 of the SFDRR, "Understanding disaster risk," which emphasizes risk assessment as a key action to inform risk reduction strategies (UNDRR, 2015). However, current social-ecological risk assessments, limited by the complex dynamics of the ecological dimension and challenges in capturing interactions between social and ecological sub-systems, inadequately address the linkages between social and ecological systems, highlighting the need for improvement to better inform disaster risks.

My research aims to improve existing multi-hazard risk assessment frameworks from a social-ecological perspective, with a focus on deltaic social-ecological systems. In the following sections, a detailed background of the research is provided, including the relationship between climate change and natural hazards, risk trends in global deltas, and information on two study deltas. Then, the historical development of vulnerability and risk assessments is summarized, focusing on the evolution of concepts and approaches related to vulnerability and risk analysis, general vulnerability and risk assessment frameworks, relevant ecosystem service research, and risk assessments in deltaic environments. Lastly, the summary of overall gaps and objectives leads to three specific research questions, followed by the structure and workflow of the thesis.

1.1 Climate change, natural hazards, and disaster risk reduction

Climate change has intensified since the mid-20th century, driven primarily by anthropogenic drivers, including deforestation, fossil fuel combustion, and agriculture (IPCC, 2021). As indicated in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), global average surface temperatures increased by 1.09°C in 2011–2020 compared to 1850–1900 (IPCC, 2022a), with certain regions experiencing warming patterns exceeding 1.5°C in at least one season (Allen et al., 2018). If unable to restrict the global temperature increases to 1.5°C, the upcoming decades will present heightened risks for human and natural systems (IPCC, 2022a). Climate change may lead to increased frequency and intensity of some natural hazards, including extreme precipitation (e.g. pluvial floods), droughts, temperature extremes (e.g. heatwaves), storms and tropical cyclones, as well as compound events (IPCC, 2021). For instance, climate change-induced sea level rise directly contributes to the submergence of low-lying coastal areas, resulting in increased flooding and saltwater intrusion (Nicholls and Cazenave, 2010). Changes in sea level rise and increasing intensity, frequency and duration of climate extreme events continue to pose risks to people and ecosystems (Fawzy et al., 2020).

According to the Peril Classification and Hazard Glossary (IRDR, 2014), hazards are classified into six categories: climatological (e.g. drought), hydrological (e.g. flood), meteorological (e.g. storms), biological (e.g., malaria), geophysical (e.g. earthquake) and extra-terrestrial hazards. Natural hazards occur frequently around the world and have increasingly led to disasters, increasing from 4,212 in 1980-1999 to 7,348 in 2000-2019—an increase of 74%, resulting in significant human and economic loss and costs (Table 1-1) (CRED and UNDRR, 2020). This surge is largely attributed to a substantial rise in climate-related disasters, including climatological, hydrological, and meteorological events (CRED and UNDRR, 2020). In terms of the adverse impact of natural hazards, China stands at the forefront globally, primarily attributed to its vast landmass, population, and scale of economic activities.

Table 1-1 Decadal average data from EM-DAT (CRED and UNDRR, 2020). Reported disasters refer to natural hazard-related disasters, including climatological, hydrological, meteorological, and geophysical hazards.

Region	Time period	Reported disasters	Total deaths	Total population affected	Recorded US$ economic losses
World	1980-1999	4,212	1.19 million	3.25 billion	1.63 trillion
World	2000-2019	7,348 (↑74%)	1.23 million (↑3%)	4.03 billion (↑24%)	2.97 trillion (↑82%)
China	2000-2019	577 (8% of world)	0.11 million (9% of world)	1.73 billion (43% of world)	0.49 trillion (16% of world)
		Rank 1st	Rank 4th	Rank 1st	Rank 2nd

Since the International Decade for Natural Disaster Reduction was launched by the United Nations in 1989 (UNCRD and UNDTCD, 1990), various approaches and policies have been implemented globally to protect against external threats such as natural hazards (Cui et al., 2021). From the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 to the Paris Agreement in 2015, the UNFCC acted to strengthen global actions to address the threat of climate change and promote risk reduction and adaptation strategies (Fawzy et al., 2020; Seddon et al., 2020). In addition, policy agreements such as the SFDRR, the SDGs, and the New Urban Agenda have also continuously advocated risk identification and enhanced disaster risk management. Understanding risk factors such as hazard characteristics, exposure of population and assets, and vulnerability has become the main consideration of risk management (UNDRR, 2015). Risk assessment, as the first priority of the SFDRR, has been progressing globally to inform regional, national and international policymakers (Ward et al., 2020). Addressing patterns in vulnerability and risk at different spatial scales is an effective tool for promoting effective disaster risk reduction and climate adaptation strategies (Sainz de Murieta et al., 2021).

1.2 Risks in deltas

This study focuses on coastal river deltas. The following section serves as a contextual background, illustrating the rationale for choosing deltaic environments as the primary focus, specifically the selected two deltas. Section 1.2.1 emphasizes the critical role of deltas in global disaster risk management, while Section 1.2.2 provides an overview of the two study deltas, highlighting the imperative to carry out comprehensive multi-hazard risk assessments.

1.2.1 Risk trends in deltas

Deltas are low-lying areas resulting from insufficient energy within the receiving basin to disperse all accumulated river-derived sediments (Anthony, 2015). They are normally classified as wave-, tide-, and river-dominated deltas according to the processes which shape the shoreline and morphology (Galloway, 1975). The first two types of deltas rely on the actions of waves and tides respectively, while river deltas are coastal topography near estuaries formed by the continual accumulation of substantial sediment transferred by distributary channels (Syvitski, 2008). Due to the highly dynamic and complex channel network that can continuously transport water, nutrients and sediments, coastal river deltas are often characterized by rich natural resources, high agricultural and fishery productivity and extensive supply of ecosystem services (Brondizio et al., 2016). They also play an important role in economic sectors, such as industry and port development, all these leading to dense population and rapid urbanization processes (GCA, 2021). Deltas cover less than 0.6% of the world's land yet are home to 4.5% of the population, as well as urban growth, with 13 of the world's 20 largest megacities located in coastal/delta regions (Adnan and Kreibich, 2016; Kuenzer et al., 2020). Their dynamic and low-lying characteristics make the delta environment susceptible to processes such as human activities, upstream changes, subsidence, sea level rise and extreme climate-related events (Nicholls et al., 2020). Combined with excessive resource extraction and environmental degradation due to human activities and urban sprawl, deltas are vulnerable to multiple natural hazards, especially hydrometeorological hazards such as river and coastal flooding (Tessler et al., 2015).

Deltas are seen as risk hotspots of global importance, depending on multiple natural hazards, dual exposures of natural and human systems, and vulnerabilities in social, economic, and ecological dimensions (Hill et al., 2020). Deltas are exposed to multiple hazards, exacerbated by anthropogenic and climate change impacts (IPCC, 2022a). Land subsidence is accelerated by natural processes of compaction and multiple anthropogenic drivers, principally groundwater abstraction, urban construction, and reduced sediment supply due to the construction of upstream dams and coastal dykes (Dunn et al., 2019). Coupled with the low gradient and elevation topography of deltas, this scenario places inhabitants at risk from relative sea-level rise (Syvitski, 2008), consequently leading to heightened natural hazards such as flooding, storm surges and salinity intrusion (Hill et al., 2020). With current and future climate change impacts, the frequency and severity of natural hazards are likely to increase and significantly affect future risk trends (Tessler et al., 2015).

The deltas’ population, economy, and natural environments are highly exposed to multiple hazards, with increased population and infrastructure being particularly adversely affected (IPCC, 2022a). In 2017, 339 million people lived in delta regions that are highly exposed to flooding, cyclones and other coastal hazards (Edmonds et al., 2020). Besides, the global population of river deltas increased by 34% between 2000 and 2017, mainly in low-income and least-developed countries according to the OECD classification (OECD, 2023), and is expected to increase by another 50% by 2050 (Edmonds et al., 2020; GCA, 2021). Population growth may lead to increased pressure on natural resources (e.g., biomass, water, and soil), challenging resource availability and potentially resulting in environmental degradation (Cardona et al., 2012). Meanwhile, relative sea level rise and the occurrence of natural hazards may further exacerbate the degradation of various ecosystems, including coastal wetlands (Nicholls et al., 1999).

In view of the dynamic characteristics of the deltaic social-ecological system, its vulnerability analysis encompasses various social, economic, and ecological aspects (Sebesvari et al., 2016). Owing to its multidimensional vulnerability and diverse social/environmental settings, the internal drivers of vulnerability manifest differentially across regional and global scales. Low-income and least-developed economies, characterized by lower levels of socioeconomic development (including inequality and infrastructure development), are often more vulnerable regions. For example, drought and other extreme events may disproportionately affect farming households whose livelihoods are highly dependent on the stability of natural ecosystems than other groups, and result in poverty and widen the poverty gaps within and between countries (Hallegatte and Rozenberg, 2017). Overall, the disaster risks linked to climate-related hazards are closely related to the trends in vulnerability driven by social dimensions (demographics, economic development, and power relations) and ecosystem destruction and degradation (Retief et al., 2016).

In summary, the choice of deltas for this study is driven by their huge economic contributions, high population density, unique natural conditions, low-lying geographic characteristics, complex SES dynamics, and management challenges. These characteristics make deltas typical SESs with complex interactions, ideal for understanding SES dynamics, analysing risk trends and climate change impacts, and improving multi-level governance and cross-sectoral management for disaster risk reduction and climate change adaptation.

1.2.2 Study area

Site 1:Pearl River Delta

The Pearl River Delta (PRD) is situated along the southern coastal area of China and consists of nine cities in Guangdong Province: Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing (Fig. 1-1). Covering a land area of 55,000 km^2 and sustaining a population of approximately 64 million (PSB, 2019), it stands out as one of China's most urbanized regions, with the largest urban agglomeration in the world (Zhu et al., 2023). The PRD region is also the most urbanized of coastal river deltas globally and expected to maintain this status under three future development scenarios (SSP1: sustainable development, SSP2: "middle-of-the-road" development, SSP3: regional rivalry), followed by the Rhine, Yangtze River (the other study area) and Chao Phraya deltas (Scown et al., 2023). The PRD is characterized by its low-lying terrain, intersected by three major rivers—the West, the Bei, and the East rivers—contributing to its agricultural and aquacultural abundance (Wu et al., 2018). Intensive human activities, including infrastructure construction, groundwater extraction, and land reclamation, have led to land subsidence (Liu et al., 2023).

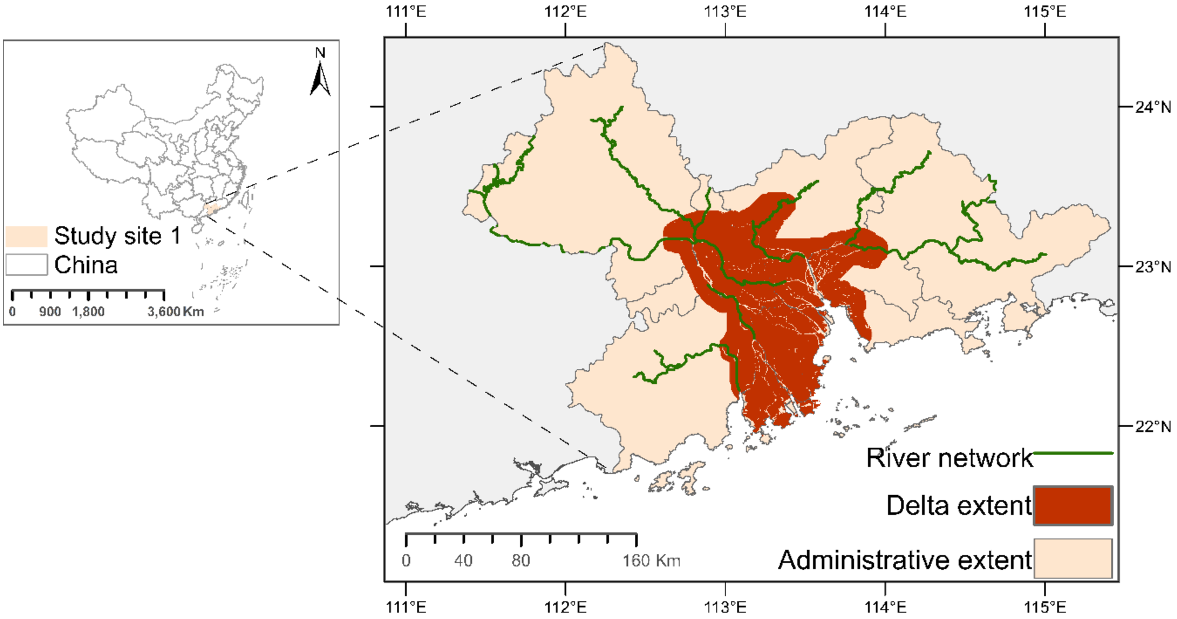

Figure 1-1 Pearl River Delta map indicating geographical delta extent (red) based on Tessler et al. (2015), administrative scope with city boundaries (yellow) from GADM (2018), and main river network (green lines) from Yan et al. (2019).

The PRD experiences a subtropical monsoon climate marked by abundant rainfall and high humidity (Yang et al., 2010). The extensive river networks could potentially exacerbate the impacts of floods, with intense runoff induced by heavy rainfall and frequent storm surges during the summer (Mei et al., 2021). Urbanization, coupled with the effects of climate change, also contributes to heightened frequency and intensity of summer rainfall, resulting in more severe flooding (Chen et al., 2021). Despite abundant rainfall, the PRD still faces water shortage due to uneven spatial and temporal precipitation distribution (Liu et al., 2011; Zhang et al., 2009). As a risk hotspot, the region is highly exposed to various natural hazards, including storm surges, pluvial flooding, typhoons, drought, and salinity intrusion, resulting in substantial losses to both inhabitants and property. In 2020, direct economic losses from storm surges alone were nearly US$700 million (DNR, 2020).

Site 2: Yangtze River Delta

The Yangtze River Delta (YRD), situated in the eastern coastal area of China (Fig. 1-2), took shape through the filling of pre-Holocene estuaries, subsequently exposed by river-sea interactions in the middle and late Holocene (Cheng et al., 2023). Characterized by a deltaic topography, the region has an extensive river network, including the Huang-Pu, the Qin-Huai, the Tiao-Xi and the Yong rivers, along with the Jing-Hang Grand Canal and the Taihu Lake Basin (Lin et al., 2023). It has received substantial sediment through river network system and exhibits sensitivity to changes in this sediment supply (Yang et al., 2003). However, the construction of the Three Gorges Dam and the implementation of the South-to-North Water Diversion Project have led to a reduction in sediment input, exacerbating erosion in the YRD (Yang et al., 2011).

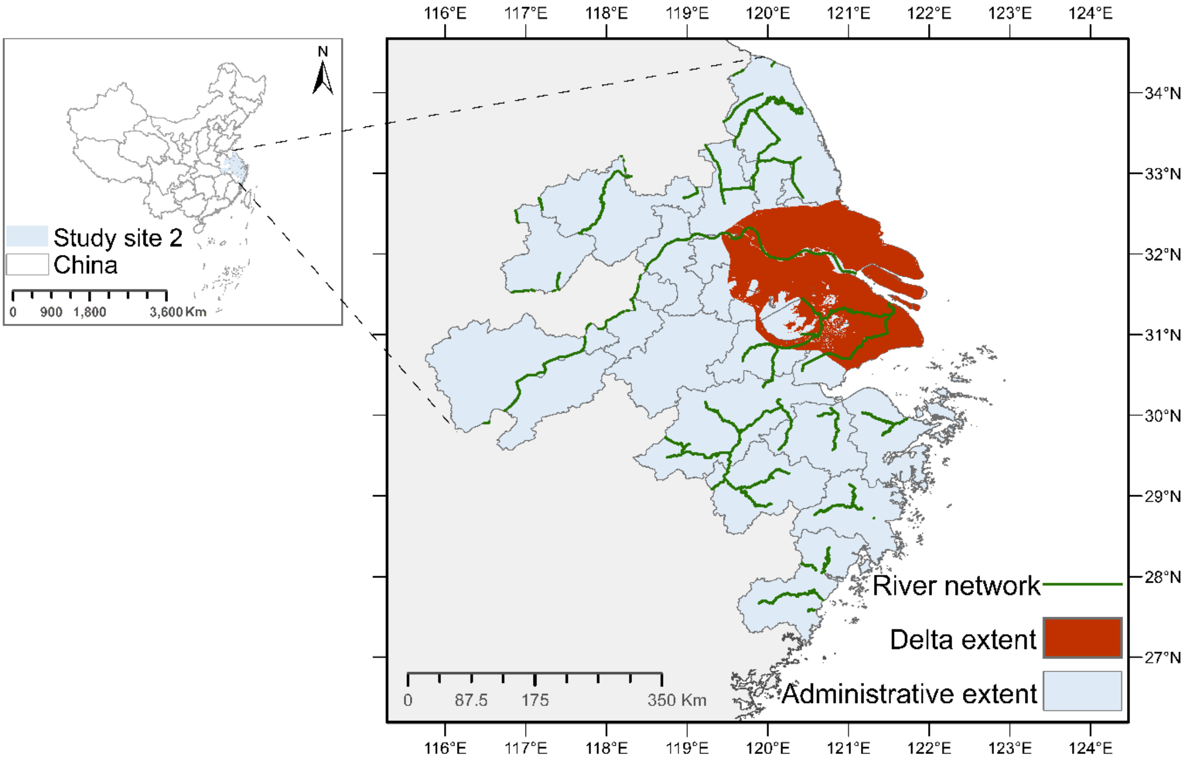

Figure 1-2 Yangtze River Delta map indicating geographical delta extent (red) based on Tessler et al. (2015), administrative scope with city boundaries (blue) from GADM (2018), and main river network (green lines) from Yan et al. (2019).

Administratively, the YRD region encompasses 27 cities, including Shanghai and parts of neighbouring Jiangsu, Zhejiang and Anhui provinces (The CPC Central Committee and General Office of the State Council, 2019). The region, comprising 2% of China's land area and hosting approximately 10% of the population, generates nearly 21% of China's Gross Domestic Product (GDP) (NBS, 2020). It is also recognized as one of the most densely populated and economically dynamic areas in both China and globally. Rapid urban expansion significantly affects water cycle processes and hydrological environments, thereby exacerbating drought risks in urban areas (Huang et al., 2023).

The YRD region also features a typical monsoon climate, rich water and natural resources—renowned for its rice production and aquatic resources (Gu et al., 2011). However, excessive rainfall subjects it to severe urban flooding, resulting in substantial economic losses (Mei et al., 2021). Furthermore, the rise in sea levels has exacerbated salinity intrusion, erosion, and storm surges, posing additional risks to food production and other critical sectors (Wang et al., 2018). The average annual direct losses from storm surges between 2011 and 2020 in the YRD reached a substantial US$297.7 million (MNR, 2021).

China is one of the countries most severely affected by natural hazard-related disasters worldwide (as shown in Table 1-1), with the PRD and YRD identified as risk hotspots owing to their distinctive deltaic geographical and economic features. Compared with other coastal river deltas, the Pearl River and Yangtze River deltas remain at the forefront globally in terms of their economic significance (GDP) and population density (Scown et al., 2023). Data collection in these two relatively developed regions is feasible due to the availability of census data, published studies, and satellite imagery. Meanwhile, China's institutional background involves multi-level governance, including national, provincial, and local authorities, as well as cross-multi-level policies. Provincial governments in regions such as the four provincial units present in the PRD and YRD have some autonomy to implement policies tailored to local conditions while addressing region-specific challenges, providing a preliminary foundation for developing and implementing risk reduction and adaptation strategies. Insights gained here can also inform global risk analysis and policy-making. While specific characteristics may vary, basic natural processes (e.g. erosion), social development (e.g. urbanization), and social-ecological coupling are common to many deltas. The approaches for understanding SES dynamics and assessing vulnerability and risks in PRD and YRD can be adapted and applied in other deltas or social-ecological systems globally. Furthermore, strategies to address the climate change crisis and promote risk reduction and adaptation strategies in these two deltas also inform practices in other deltaic and coastal regions. Effectively managing and reducing risks in these areas holds strategic importance in reducing hazard impacts and achieving sustainable development at the regional, national, and global levels.

1.3 Historical development of vulnerability and risk assessment

This section reviews the literature on vulnerability and risk assessment (research practice and theory progress worldwide) and examines the methodology utilized in empirical research across various scales. Section 1.3.1 outlines the historical evolution of vulnerability and risk theories and concepts, establishing the primary focus of this thesis. Section 1.3.2 mainly summarizes the progress of vulnerability and risk assessment frameworks, including their practice at different scales, hazard types, and environmental context settings. Section 1.3.3 discusses the existing theories and practices of ecosystems and their services in vulnerability and/or risk assessment. Section 1.3.4 provides an overview of the progress made in vulnerability and risk assessments in deltaic environments. The aim here is to provide a detailed theoretical background and empirical motivation for the design of this study, some of which may be repeated in the three papers (Chapters 2, 3, and 4).

1.3.1 Evolution of approaches to vulnerability and risk assessment

The concept and characteristics of vulnerability have evolved over the decades according to different focuses and scales of research (Adger, 2006; Birkmann, 2013; Fekete et al., 2010; Hinkel, 2011). From the perspective of social geography, vulnerability concept could be divided into external and internal structures (Bohle, 2001). The external structure mainly covers three overlapping areas: hazard-centred theory (elements of exposure to risks) (Ciurean et al., 2013; Dewan, 2013), political economy and human ecology (including social inequality, population dynamics, capacity of environmental management) (Cutter, 1996; Duncan et al., 2017), and entitlement theory (a lack of resources necessary to secure people's livelihoods, e.g. food and water) (Adger, 2006; Ciurean et al., 2013). The internal side refers to the capacity to manage and respond to hazards, and is related to approaches such as crisis and conflict theory (capacity to manage resources and conflicts), theory of action, and access to assets model (Bohle, 2001; Ciurean et al., 2013).

Current methods of vulnerability analysis mainly adopt a comprehensive interdisciplinary perspective to fully understand and address vulnerability, particularly with a consistent focus on social-ecological systems (SES) (Folke et al., 2005; Preston et al., 2011; Vogt et al., 2015). Natural systems refer to a wide range of biophysical processes, while social systems encompass the human use of natural resources based on social structures, institutions, and knowledge systems (Berkes et al., 1998). Vulnerability is thus developed into two main dimensions (Ciurean et al., 2013; Dewan, 2013; Preston et al., 2011; Sebesvari et al., 2016; Shukla et al., 2018): (1) Biophysical and ecological factors. These factors include physical or functional characteristics such as the propensity of infrastructure, structures and services to be affected by potential hazards. The ecological and environmental dimension refers to the interaction of various ecosystems, the supply of ecosystem services, and the capacity to cope with and recover from the impacts of hazards, and may include factors such as topography, climatic conditions and land cover; (2) Socioeconomic and institutional factors. Social factors are mainly related to the coping capacity of humans and the community, such as infrastructure and demographics (e.g. gender, age, and education). Economic vulnerability refers to those sectors of the economy and trade that are affected by hazards that may reduce productivity and income. Institutional aspects refer to policies and strategies in response to risk management, such as risk reduction policies and capital investment. To address the coupled dynamics of natural and social systems, the theory of vulnerability on SES has been continuously practised in the fields of climate change impact, risk management and related resilience research (Birkmann et al., 2013; Kuenzer et al., 2020; Thiault et al., 2018; Turner et al., 2003a; Vázquez-González et al., 2021).

Vulnerability and risk assessment approaches have been developed based on the theory of vulnerability and risk analysis, mainly including the ‘pressure and release’ model, physical vulnerability, social vulnerability, and integrated SES methods (Peng et al., 2023, also Chapter 2; Preston et al., 2011). The pressure and release model, which considers physical/biological hazards as the root cause of vulnerability, coupled with further vulnerability accumulation in the social context, eventually leading to disasters, is usually applied at region-specific scales (Wisner et al., 1994). It captured the causes, drivers, and social processes of vulnerability, viewing risk as a function of hazard and vulnerability (Risk = Hazard × Vulnerability), but failed to address the dynamic connection and feedback between various biophysical and social processes (Birkmann, 2013; Preston et al., 2011). Physical vulnerability assessment, which mainly emphasizes the impact of hazardous events and the exposed physical structures and other characteristics, can also be applied to map the ecosystem vulnerability, relying on various computer modelling techniques (Dewan, 2013; Döll, 2009). If physical vulnerability focuses on identifying hazard impacts and environmental drivers, social vulnerability seeks to measure the underlying socioeconomic factors that affect the ability of humans and societies to respond to natural hazards (Cutter et al., 2003; Kirby et al., 2019; Ogie et al., 2018). The final integrated assessment framework argues that the key to vulnerability analysis lies in understanding the interaction between social characteristics and biophysical processes at different spatial scales, emphasizing attention to coupled SES (Kok et al., 2016; Sebesvari et al., 2016). Comprehensive SES assessment methods, limited by the complexity of SES interactions at different spatial and temporal scales, are being further developed (Berrouet et al., 2018; Rissman and Gillon, 2017), detailed in Section 1.3.2.

Vulnerability and risk assessments have grown rapidly over the past few decades to provide information to support adaptation and risk reduction strategies in the context of climate change and/or specific climate hazard research (Frazier et al., 2014; Gallina et al., 2016; Garschagen et al., 2021; Hallegatte and Rozenberg, 2017; Young et al., 2015). According to risk framing presented in the IPCC Sixth Assessment Report (2022a) (as shown in Fig. 1-3), the historical development of risk assessment mainly focuses on four main questions:

1. What impacts are being experienced? This refers to risk assessment practices, including the analysis of exposure and vulnerability in human and ecological systems, along with drivers of climate-related hazards.

2. What responses are being undertaken? This relates to the design and implementation of adaptation measures to realised risks.

3. What future risks are of greatest concern? Eight ‘representative key risks’ are summarized, including risks to the low-lying coastal SES, such as coastal river deltas. These studies primarily involve the analysis of risk components like exposure, vulnerability and adaptation.

4. What are the limits to adaptation? The IPCC Sixth Assessment Report newly introduces the concept of limits to adaptation to summarize factors influencing the planning and implementation of adaptation actions, such as limited financial resources of social systems and lack of capacity of natural systems to adapt to biophysical changes. Moreover, due to the dynamic and multi-dimensional characteristics of SES risks, current practices still lack empirical evidence for assessing limits to adaptation.

Figure 16.1 illustrates the elements covered by the chapter, which can be summarised as four key questions

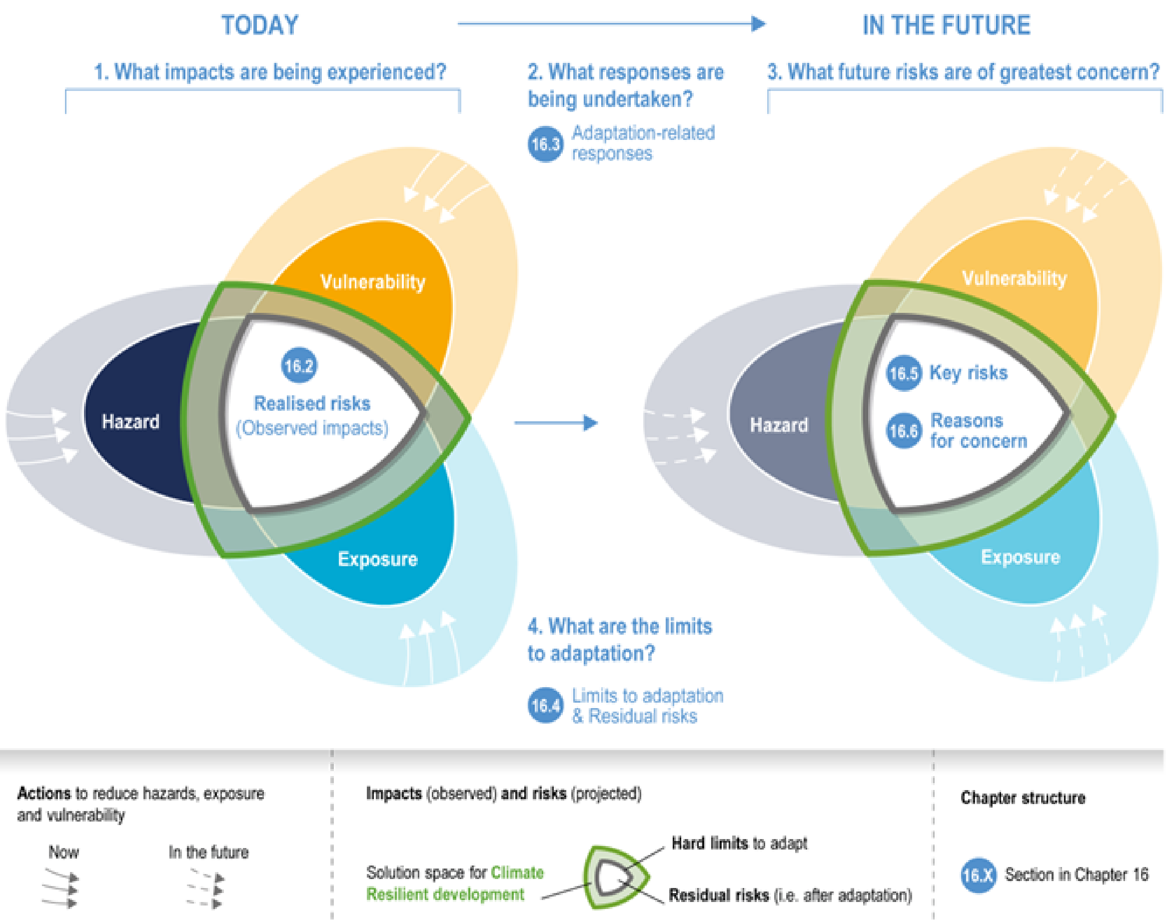

Figure 16.1 | Illustrative storyline of the chapter highlighting the central questions addressed in the various sections, from realised risks (observed impacts) to future risks (key risks and reasons for concern), informed by adaptation-related responses and the limits to adaptation. The arrows illustrate actions to reduce hazard, exposure and vulnerability, which shape risks over time. Accordingly, the green areas at the centre of the propeller diagrams indicate the ability for such solutions to reduce risk, up to certain adaptation limits, leaving the white residual risk (or observed impacts) in the centre. The shading of the right-hand-side propeller diagram compared with the non-shaded one on the left reflects some degree of uncertainty about future risks. The figure builds on the conceptual framework of risk–adaptation relationships used in SROCC (Garschagen et al., 2019).

Figure 1-3 Schematic framing among the hazards, exposure, and vulnerability producing risk. Taken with copyright permission, from Figure 16.1 of Chapter 16: Key Risks across Sectors and Regions in Climate Change 2022: Impacts, Adaptation and Vulnerability (IPCC, 2022a).

This research mainly involves the first three questions mentioned above: conducting risk assessments in two deltas of greatest concern, identifying regional risk hotspots requiring attention, and analysing existing adaptation policies, accompanied by suggested adaptation strategies. ‘Risk’ in this study refers to the potential impacts resulting from the interaction of multiple natural hazards, exposure and vulnerability of human and natural systems (IPCC, 2022b), which is often expressed as Risk = Hazard × Exposure × Vulnerability (IPCC, 2014). These processes and impact/consequences of risks are driven by and interact with the natural system and social factors. The definitions of terms used in this thesis are provided in Table 1-2.

Table 1-2 Working definitions in this research.

Term	**Definition**
Risk	'Risk' in this study refers to the potential impacts resulting from the interaction of multiple natural hazards, exposure and vulnerability of human and natural systems (IPCC, 2022b).
Hazard	"The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources (IPCC, 2022b, p. 2911)." In this study, the hazard component represents the potential occurrence of one or multiple natural hazard events that may cause loss to the components of social-ecological systems.
Exposure	"The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC, 2022b, p. 2908)." In this study, exposure refers to the extent to which these elements may be adversely affected to one or multiple natural hazards (Hagenlocher et al., 2018).
Vulnerability	"The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2022b, p. 2927)."
Susceptibility	The internal propensity of an element of social-ecological systems to be adversely affected when exposed to one or multiple natural hazards (Sebesvari et al., 2016).
Coping capacity	"The ability of people, institutions, organisations and systems, using available skills, values, beliefs, resources and opportunities, to address, manage and overcome adverse conditions in the short to medium term (IPCC, 2022b, p. 2904)."
Adaptive capacity	The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences (MA, 2005).
Ecosystem robustness	It represents the capacity of an ecosystem to stabilise various ecological functions and reduce risks (Damm, 2010).
Ecosystem service	"Ecosystem services are defined as the benefits that people obtain from ecosystems (MA, 2005, p. V)." In this thesis, it emphasizes the ecological

	outcomes that can benefit human well-being, which are classified as provisioning, regulation & maintenance and cultural services.

Assessing vulnerability and risk requires the establishment of a clear theoretical and conceptual framework, and the historical development of vulnerability and risk assessment outlined above provides the following main approaches for this study: (1) understanding the role and implementation process of integrated risk management in reducing the adverse impacts of natural hazards and climate change; (2) comprehensively capturing the basic elements of social-ecological vulnerability and risk; (3) developing an appropriate vulnerability and risk framework for SES to better identify and reduce key vulnerabilities and risks according to environmental setting and priority targets.

1.3.2 General vulnerability and risk assessment frameworks

Risk assessment in the context of climate change adaptation and risk reduction measures emphasizes a social-ecological approach, regarding vulnerability as a characteristic of SES (Adger, 2006; Birkmann et al., 2013; Ostrom, 2009). The social-ecological approach is an integrative perspective that considers the interconnections and interdependence of social systems and ecosystems, and starts to influence major policy frameworks (e.g. SDGs recognize the linkages between social-ecological aspects of sustainable development) (Fischer et al., 2015). Compared with solely social or ecological approaches, it holds advantages in a comprehensive understanding of SES dynamics, improved policy and management strategies, interdisciplinary knowledge integration, inclusive stakeholder engagement, and long-term sustainability. This approach primarily focuses on the coupling process from the socio-economic development and the impact of environmental changes on SES to fully understand the exposure and susceptibility of the overall system. Resilience refers to the capacity of interconnected SES to cope with, adapt to, and recover from the impacts of hazards (IPCC, 2022b), is considered by some as the opposite of vulnerability (Kelman et al., 2017), and has also been integrated into some existing vulnerability analyses as a component, such as the framework proposed by Turner et al. (2003a). Based on this, a number of vulnerability and risk assessment frameworks have been developed in recent years, which have continuously enriched the various stressors and response pathways of vulnerability analysis (Ciurean et al., 2013).

Turner et al. (2003a) proposed a vulnerability framework linked to sustainability science, which shows the exposure, sensitivity and resilience components of vulnerability and addresses the disturbance and stress produced by the processes of the coupled human-environmental system. This framework seeks to analyse vulnerability and its components at different spatial scales and provides a theoretical basis for vulnerability assessment of coupled systems. Its application included two case studies in Mexico and one in the Pan-Arctic region, engaging local stakeholders' knowledge (Turner et al., 2003b). These cases illustrated the impact of external environmental factors, such as hurricane-induced crop damage, on reshaping vulnerability, emphasizing the framework's role in identifying interactive processes of SES (Turner et al., 2003b). Damm (2010) modified the framework by replacing the original 'resilience' component in vulnerability with the ‘capacities’ component consisting of ecosystem robustness, coping and adaptive capacities. Among them, coping and adaptive capacities mainly involve the socioeconomic elements of social systems, and ecosystem robustness added to the vulnerability domain can reflect the responses of ecosystems.

Based on their 2007 multitier framework for analysing an SES, Ostrom (2009) updated a nested framework showing the interrelated relationships among multiple subsystems of SES with social, economic, political and related ecosystem settings, especially reflecting the role of governance/institutional systems. This research reflects that long-term sustainable development requires individual, community and social systems consistent with local conditions, depending on enforcement, monitoring, and site-adaptive policies (Ostrom, 2009).

The MOVE framework (project Methods for the Improvement of Vulnerability Assessment in Europe) was developed by connecting multi-dimensional components of vulnerability and integrating existing frameworks to discuss how to reduce risk and improve adaptive capacity in the context of natural hazards and climate change (Birkmann et al., 2013). This framework classifies key concepts of vulnerability and links to the ‘adaptation’ component of risk management, again illustrating how vulnerability relates to potential impact (risk) (Birkmann et al., 2013). Although the specific application process and detailed indicator list are not provided, most components of the MOVE framework could be a basis for the identification and selection of indicators, and are widely applied in case studies for vulnerability and risk assessment to natural hazards (Hamidi et al., 2020; Jackson et al., 2017; Lianxiao and Morimoto, 2019; Welle et al., 2014).

Research on single-hazard risk focuses on assessing the potential impacts of an individual hazardous event, usually at a regional scale with a time period (Gallina et al., 2016). Many studies around the world have adopted a single-hazard approach to determine the vulnerability and risk from a specific natural hazard, especially for flooding, droughts, cyclones, and storm surges (Abson et al., 2012; Abu El-Magd et al., 2022; Fakhruddin et al., 2022; Feyen et al., 2012; Kirby et al., 2019; Liu et al., 2022; López-Angarita et al., 2014; Lung et al., 2013; Muis et al., 2016; Ouma and Tateishi, 2014; Prabnakorn et al., 2019; Santini et al., 2010). Considering that the SES are typically affected by multiple hazards and single-hazard risk cannot be managed individually when developing risk reduction strategies, managing these risks in an integrated manner is now emphasized (IPCC, 2022a).

As a consequence, there is a growing interest in focusing on the characterisation and management of multi-hazard risk rather than single-hazard research in vulnerability and risk assessments (Gallina et al., 2016; Kappes et al., 2012; Šakić Trogrlić et al., 2022). Greiving et al. (2006) introduced a risk assessment approach that integrates multiple hazards, spatial perspectives, and multi-dimensions of social, economic and ecological factors. The construction of a risk index facilitates the integration of interdisciplinary and cross-sectoral knowledge, while the combination with geospatial techniques can realize the visualisation of risk components, thereby enhancing risk identification and management. Kloos et al. (2015) proposed an SES risk assessment framework in a multi-hazard context for West Africa, built on the work of Birkmann et al. (2013), Chapin et al. (2010), Damm (2010), and Turner et al. (2003a), which links dynamic concepts of vulnerability and resilience, and developed in conjunction with existing frameworks through explicit multiple hydro-climatic hazard settings. Centred on SES, the framework captures the interactions and responses between social and environmental subsystems at different spatial scales (community, sub-national and national) (Kloos et al., 2015). Based on the conceptual framework, a systematic process of multi-scale participatory indicator development is designed to develop the indicator list, combining qualitative and quantitative methods to assess the risks in the West African region (Asare-Kyei et al., 2015).

Multi-hazard risk assessment frameworks can capture various hazard stressors and reflect the interactions between SES processes in multi-hazard scenarios, thereby providing support for developing adaptation measures to better address future climate challenges. Most vulnerability studies focus on either social systems or ecosystems, ignoring the connections between social and ecological sub-systems (Berrouet et al., 2018; Olander et al., 2018). Natural hazard events would disturb the ecosystems with their functions and services, and affect the stability of social subsystems; meanwhile, the social systems also affect the integrity of ecosystems (IPCC, 2022a; Berrouet et al., 2018). Due to the inherently complex hierarchical and functional relationships of ecosystems, it is challenging to develop and quantify key indicators of ecosystem vulnerability, which also leads to the lack of indicators of ecosystem vulnerability within the SES risk assessment frameworks (Beroya-Eitner, 2016). Depietri (2020) compared and clarified that the main difference between well-adapted and degraded SES is the loss of ecosystem services, which means that the capacity to cope and recover from hazardous events is also reduced in a degraded SES. The above studies and reviews inspire future practices to explore more the role of ecosystem services as risk drivers to link socioeconomic aspects and ecological integrity.

The most common approach in vulnerability and/or risk assessment is a combination of an assessment framework consisting of vulnerability and risk components and an indicator-based approach (Anelli et al., 2022; Bevacqua et al., 2018; Nguyen et al., 2019; Sano et al., 2015), also applied by the aforementioned studies (Garschagen et al., 2021; Greiving et al., 2006; Kloos et al., 2015). From global or national to regional levels, a series of practical applications with indices have been implemented, such as World Risk Index (Welle and Birkmann, 2015), Social Vulnerability Index (Cutter et al., 2003), INFORM Risk Index (Marin-Ferrer et al., 2017), and Global Delta Risk Index (Hagenlocher et al., 2018). Risk indices can facilitate the capturing of multidimensional characteristics of potential risks and provide quantitative measures that can be tracked across time and regions (Garschagen et al., 2021). Vulnerability exhibits multiple structures, allowing for the identification of key components into hazard-dependent (direct physical impacts of hazards: physical exposure) and hazard-independent (indirect consequences: susceptibility of socioeconomic factors, lack of coping and adaptive capacity) categories (Carreño et al., 2007). A modular indicator-based approach based on this is broadly applicable to environment-specific (multi-)hazard settings, making it easier to identify and extend specific hazard-related vulnerability indicators and conduct vulnerability and risk assessments in other given environments (Hagenlocher et al., 2018). Meanwhile, understanding and assessing risks requires the participation of diverse stakeholders, which can not only integrate scientific and local knowledge, but also facilitate the assessment of co-benefits and trade-offs of adaptation measures (IPCC, 2022a). The involvement and priorities of experts and local stakeholders have been emphasized in several risk assessments, such as indicator identification, weight assignments, and social perception (de Ruiter and van Loon, 2022; Hagenlocher et al., 2018; Hochrainer-Stigler et al., 2023; Ouma and Tateishi, 2014; Pathan et al., 2022; Qiu et al., 2015; Romagosa and Pons, 2017).

1.3.3 The role of ecosystems and their services in risk assessment and disaster risk reduction

Since the 1990s, it has been recognized that ecosystems provide life support as natural capital, and their services are critical to human well-being (Costanza et al., 1997; Daily, 1997). The publication of the Millennium Ecosystem Assessment (MA) has strengthened the understanding of the link between society and ecosystem changes, further meeting the scientific information needs in ecosystem management and decision-making (Carpenter et al., 2006). Ecosystem services are defined as 'the benefits that people obtain from ecosystems' and are classified into supporting, provisioning, regulating, and cultural services (MA, 2005). Linking the supply and trade-offs of various kinds of ecosystem services to a variety of social, economic, ecological, technological, and governance factors allows social-ecological analysis (Andersson et al., 2015; Meacham et al., 2016; Torralba et al., 2018). In addition to the MA, initiatives such as the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES, 2019), the Economics of Ecosystems and Biodiversity (TEEB) (Sukhdev and Kumar, 2008), and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018), provide strong theoretical and operational foundation for ecosystem services identification and quantification.

In recent years, facing the loss and degradation of ecosystem services, there has been an increasing interest in exploring how SES have been affected by environmental stress or natural hazards and the corresponding influencing factors and processes (Bhattachan et al., 2018; Mononen et al., 2016; Schröter et al., 2005). Current scientific analysis reveals that hazardous events and other climatic drivers affect the biophysical and chemical conditions of the natural environment and exacerbate the impact of anthropogenic drivers such as sedimentation, leading to changes in ecosystem structure and processes, and ecosystem services supply (IPBES, 2019; IPCC, 2022a). In essence, ecosystem services are linked to climate change through a series of pathways such as climate drivers - ecosystem structure and processes - ecosystem services - human well-being.

In the context of environmental management, ecosystem services research falls into two main categories: the assessment and quantification of ecosystem services, with applications extending to vulnerability assessments; and the practices of ecosystem services in planning and decision-making (de Groot et al., 2010). Research in analysing the social outcomes of ecosystem services (such as economic value) to characterize the response of SES to natural hazards has made progress (Beier et al., 2008; Berrouet et al., 2018; Olander et al., 2018).

Based on the integrated perspective of SES analysis, Collins et al. (2011) used the 'pressure and release' model to explore the interaction of external climate drivers, biophysical, and social domains, in which ecosystem services play a role in linking and integrating the dynamics or processes between ecosystem function and human outcomes. Ciftcioglu (2017) conceptualized the resilience of SES landscapes by analysing drivers and changes in several ecosystem services to classify the interrelationships between biophysical and social templates, thereby overcoming the isolated consideration of sub-systems in SES research. It considered the role of ecosystem services in enhancing SES resilience and human well-being, but did not discuss how to integrate the concept of ecosystem services into spatial planning and integrated management.

Based on the vulnerability framework of Turner et al. (2003a) and other theories on ecosystem services, Mansur et al. (2016) proposed a conceptual vulnerability framework for the Amazon Delta and Estuary and used the Analytic Hierarchy Process (AHP) to assess the flood exposure, infrastructure, and socioeconomic conditions of vulnerability in urban spaces. This study involved and emphasized the importance of ecosystem services in linking socioeconomic and natural variables in the framework, but did not include ecosystem services in vulnerability assessment. Qiu et al. (2015) developed a vulnerability index that incorporates a sensitivity sub-component using the coverage of five ecosystem types (e.g. wetland proportion) to determine the levels of ecosystem services provisioning. Obviously, this method oversimplified the consideration of ecosystem services.

Studies on ecological risk also use ecosystem services at multiple scales to quantify the potential impact of ecological and environmental conditions on vulnerability (Asmus et al., 2019; Bevacqua et al., 2018; He et al., 2018). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was developed to map and value services from natural systems (Sharp et al., 2014), which is widely used in assessing ecosystem services and their risks (Chung et al., 2015; Willaert et al., 2019). Based on the InVEST Coastal Vulnerability model, an index-based approach with the role of ecosystem services was presented to map natural habitats and assess the coastal risks (Silver et al., 2019). It seeks to identify regions with high potential and guide decision-makers to conduct nature-based approaches to enhance coastal resilience and adaptive capacity (Silver et al., 2019). By dividing the vulnerability analysis into a combination of biophysical exposure, sensitivity, and adaptive capacity indices, the InVEST tool was used to estimate coastal exposure based on biophysical characteristics (Zhang et al., 2020). Social-ecological risk research incorporating ecosystem services is rare. Although Lilai et al. (2016) proposed an integrated multi-dimensional SES approach to estimate flood risks in a coastal city, it would be an oversimplification to directly equate exposed ecosystem services with ecological risk.

From ecological supply (ecological function and elements) to ecosystem services that humans use or enjoy, analysis of ecosystem services can consider both the pathways of ecosystem service flow and the participation of human demand (Tallis et al., 2012; Wu, 2013). Beneficiaries of ecosystem services usually differ in socioeconomic characteristics and adaptive capacity when facing external disruptions (Jones et al., 2016). Therefore, in addition to quantitative tools, qualitative methods are also widely used in the evaluation of ecosystem services (Bouahim et al., 2015; Khan et al., 2019; Seppelt et al., 2011). Stakeholder engagement can be understood as an approach for linking ecosystem function to human well-being, including ecosystem service identification and perception, informing adaptation planning at the regional level, and assigning weights to indicators based on scientific or local knowledge (Seppelt et al., 2011). For example, Depietri et al. (2013) carried out a vulnerability assessment to heat waves based on the MOVE framework in Germany, which collected stakeholders' perceptions on the capacity of local ecosystem services to mitigate heatwave impacts and also provided additional local knowledge for integrating social and ecological dimensions. In another example, ecosystem services identified and perceived by experts and other stakeholders are considered key elements in assessing environmental risks under climate change (Asmus et al., 2019).

Ecosystem services are closely associated with concepts such as ecosystem-based adaptation (EbA), disaster risk reduction (DRR), climate change adaptation (CCA) and the SDGs (IPCC, 2022a). The supply of ecosystem services is critical to maintaining ecosystem health and integrity and social benefits, and their positive role in mitigating the effects of natural hazards has received increasing attention (Fisher et al., 2009; Hossain et al., 2017; Kandziora and Burkhard, 2013; Lilai et al., 2016; Myers et al., 2019). Conducting assessments of ecosystem services that link ecological processes with social and economic aspects is conducive to proposing ecosystem-based management measures (Tallis and Polasky, 2009). Meanwhile, linking ecosystem services to EbA and other strategies could contribute to joint benefits faced by climate change adaptation (Arkema et al., 2017; Tran and Brown, 2019).

In summary, current research involving ecosystem services in vulnerability and risk assessment has the following main limitations: (1) Although recognizing and emphasizing the importance of ecosystem services to better characterize the linkages between social and biophysical environments, ecosystem services indicators are not fully incorporated into SES studies. As mentioned previously, only a few practices integrate ecosystem services into ecological risk assessments, primarily through the evaluation of land use changes (Fang et al., 2023; Liang and Song, 2022; Wang et al., 2021). (2) Some studies directly use the estimated value of selected ecosystem services to represent vulnerability. Given multi-dimensional characteristics of vulnerability introduced in Section 1.3.1, this approach may prove inadequate in fully illustrating the SES response to natural hazards. Specifically, the absence of established vulnerability components, including social susceptibility (e.g. infrastructure), could result in insufficient insights into the social and economic dimensions. Excluding using the ecosystem services framework as an independent assessment method (including the InVEST model), ecosystem service indicators have not yet been integrated into SES-based vulnerability and risk assessment framework. Linking to Section 1.3.2, one of the challenges of current SES vulnerability research is the insufficient consideration of the ecosystem. It may be a breakthrough to deduce the dynamic processes and ecological mechanisms of ecosystem services and then incorporate them into a risk framework to describe coupled SES dynamics more precisely.

1.3.4 Vulnerability and risk research in deltas

Research on deltas at a global scale is emerging, seeking to understand the spatial dynamics of delta risks. Tessler et al. (2015) undertook a systematic global risk assessment resulting from fluvial and coastal flooding in 48 coastal deltas, with an indicator-based approach allowing the estimation of future scenarios with infrastructure investments. In a recent study, a detailed analysis of 49 deltas using 13 socioeconomic and geophysical variables, guided by risk components developed by Tessler et al. (2015), revealed future risk in deltas and the influence of deltas on the global sustainable development agenda (Scown et al., 2023). Additionally, a separate study employed cluster analysis on 48 deltas, considering anthropogenic pressures and environmental indicators, to enhance the sustainable management of these important regions (Tessler et al., 2016). The indicator-based risk assessment proves to be an effective method when conducting comparative analyses between large deltas.

Flooding stands out as an exceptionally destructive natural hazard, for instance, accounting for 44.9% of economic losses from natural hazards worldwide in 2022 (CRED, 2023a). It has prompted extensive attention to the analysis and management of flood-related risks, both at the global (Klijn et al., 2015; Trigg et al., 2016; Van Coppenolle and Temmerman, 2019), and individual delta scales (Chan et al., 2021; Dai et al., 2020; Frick-Trzebitzky et al., 2017;

Kirby et al., 2019; Mansur et al., 2016; McElwee et al., 2017; Yang et al., 2015). In addition, there are several studies at the delta or local scales, focusing on cyclones (Zhou et al., 2021), storm surges (Neumann et al., 2015), erosion (Li et al., 2015), sea level rise (Zhao et al., 2021), drought (Damian et al., 2023), and pollution (Zhang et al., 2013; Zhu et al., 2019).

Considering that SES often face multiple natural and anthropogenic hazardous events, progress has also been made in advancing multi-hazard risk research in deltas, primarily through indicator-based approaches that measure separate indices (e.g., single-hazard exposure), which are then aggregated into an integrated risk index (Islam and Al Mamun, 2020; Murshed et al., 2022). Sebesvari et al. (2016) proposed an inclusive risk assessment framework to understand the characteristics of hazard and vulnerability components for deltaic social-ecological systems at various spatial scales. In this framework, vulnerability consists of four subcomponents: social susceptibility, coping and adaptive capacity, ecosystem susceptibility, and ecosystem robustness. Building on this framework, the Global Delta Risk Index (GDRI) was introduced, complemented by a modular indicator library and collaborative expert consultations (Hagenlocher et al., 2018). This innovative approach was employed to undertake a comparative risk assessment of the Amazon, Ganges-Brahmaputra-Meghna (GBM), and Mekong deltas, taking into account multi-hazard settings (cyclones, drought, flooding, salinity, storm surges, and pollution). Structured consideration of social and ecosystem subsystems not only offers advantages to observing sustainability issues and feedback on risks posed by social activities and ecosystems, but also allows for capturing differences in vulnerability. The GDRI and its comprehensive indicator library was further applied in the Mississippi delta to inform the coastal flood risk profile and multi-hazard (coastal flood, hurricane, and drought) vulnerability, while also examining the adaptability and transferability of this approach (Anderson et al., 2021). However, like other vulnerability and risk assessment practices mentioned in 1.3.2, current research and indicator systems for deltas inevitably pay more attention to social vulnerability. A review of vulnerability assessment for deltas found that 84% of identified vulnerability indicators described the vulnerability of social systems (Sebesvari et al., 2016). Overall, some vulnerability indicators associated with the ecological dimension, such as land use or cover changes, offer an understanding of ecosystem service levels. Nevertheless, there is a lack of research explicitly incorporating considerations of ecosystem services into conceptual frameworks and risk assessments for deltas. The role of ecosystems and their services is more prominently reflected in the design of nature-based solutions and ecosystem-based disaster risk reduction, exemplified by an emphasis on wetlands restoration in strategies for coastal disaster risk reduction (Rojas et al., 2022).

1.4 Objectives, research questions, and thesis structure

The above overview suggests that there are existing vulnerability and risk assessment frameworks that can address coupled SES exposed to natural hazards, but there are imbalanced considerations between social and ecological vulnerability. Recent frontiers in vulnerability and risk assessments include achieving a more comprehensive understanding of complex SES interactions to better reflect real-world dynamics, as well as adopting a multi-hazard perspective to facilitate more integrated and targeted management strategies. Social-ecological vulnerability assessment could take into account ecosystem services to capture and quantify the interactive mechanisms between SESs. Meanwhile, the systematic inclusion of ecosystem services in the addressed social and environmental contexts also needs to be carefully considered. Beyond the research gaps in the risk assessment field, there remains a lack of practical applications of multi-hazard risk assessments in PRD and YRD regions, and significant knowledge gaps in identifying the drivers of multi-scale SES vulnerability. Addressing these gaps is crucial for advancing regional and local risk reduction strategies. In view of this, and with the intent of conducting a more comprehensive assessment of vulnerability and risk in targeted deltas, this study aims to address the research gaps by incorporating the role of ecosystem services in SES vulnerability and risk assessment approaches, through three objectives to (1) provide a better representation of dynamic interplay characterizing SES, (2) facilitate an improved risk assessment to multiple natural hazards, and (3) provide supporting information for policy-makers and decision-makers to develop disaster risk reduction and climate change adaptation strategies aligned with assessment results.

In order to fulfil the above research objectives of constructing a deltaic vulnerability and risk assessment framework and mapping the risk profile in the Pearl River and Yangtze River deltas, this study addresses three overarching research questions (corresponding to three papers), as illustrated in Fig. 1-4.

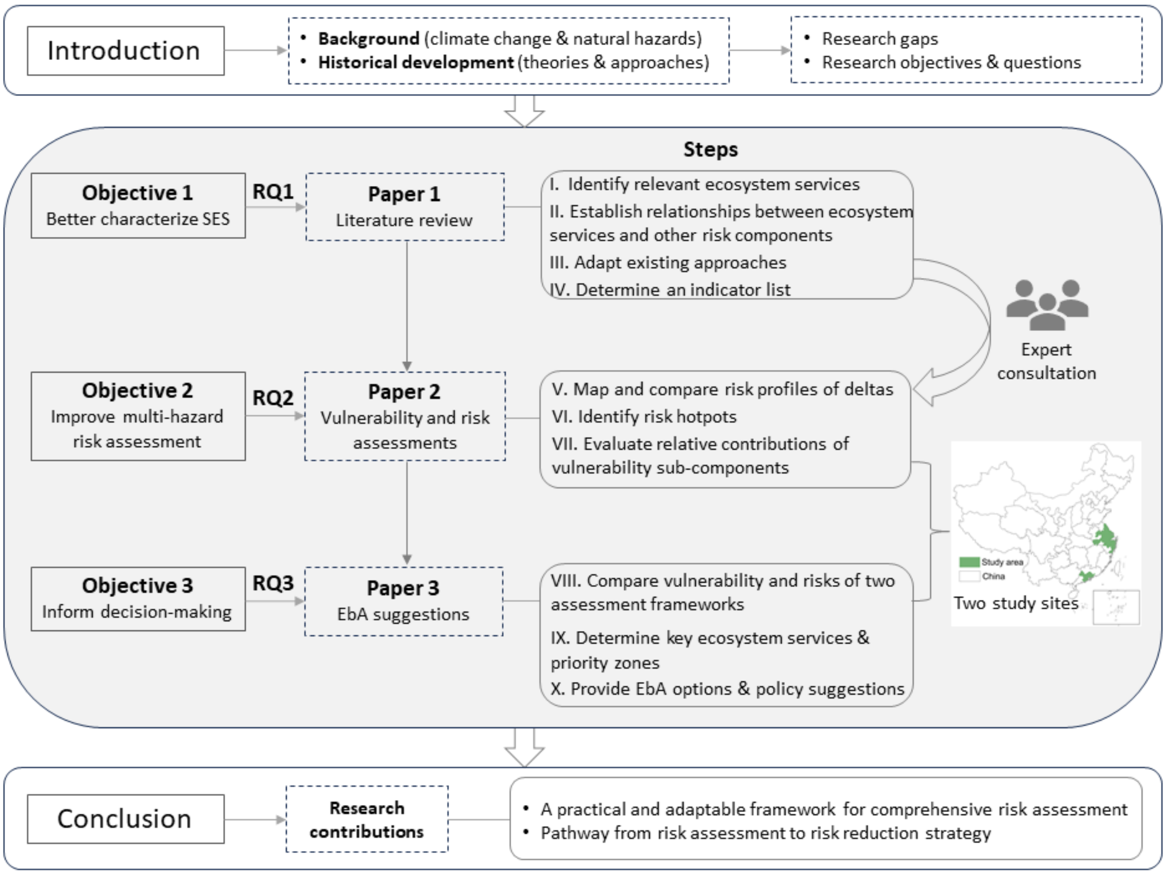

Figure 1-4 Structure and workflow of the thesis. The dotted box in the middle column is the main content of each chapter, which includes the main steps (solid column on the right). After a comprehensive review of previous research, Chapter 2 (Paper 1) introduces a novel risk assessment framework and identifies a set of indicators. These indicators are subsequently used for risk assessment in the Pearl River and Yangtze River deltas following expert consultation (Chapter 3/Paper 2). Chapter 4 (Paper 3) further explores the role of ecosystem services in shaping ecosystem-based adaptation strategies.

Within this context, specific research steps are detailed below the titles of the respective papers, aligning with the research questions addressed in the three papers.

RQ1. How can we best integrate ecosystem services into SES vulnerability and risk assessment to improve current vulnerability and risk assessment approaches?

Paper 1: A framework for integrating ecosystem services indicators into vulnerability and risk assessments of deltaic social-ecological systems (Peng et al., 2023).

Step I. Identify ecosystem services relevant to risk assessments in deltaic and coastal areas;

Step II. Establish the relationships between ecosystem services and other vulnerability components in the risk framework;

Step III. Adapt existing approaches for vulnerability and risk assessment of SES to allow for the inclusion of ecosystem services;

Step IV. Determine an appropriate list of ecosystem service indicators for future research.

RQ2. What are the general vulnerability and risk profiles in China's two major deltas (Pearl River and Yangtze River deltas) when exposed to multiple natural hazards and when considering explicitly ecosystem services?

Paper 2: Incorporating ecosystem services into comparative vulnerability and risk assessments in the Pearl River and Yangtze River deltas, China (Peng et al., 2024a).

Step V. Map and compare the overall vulnerability and risk profiles of the Pearl and Yangtze River deltas;

Step VI. Assess which regions in these deltas are at higher risk levels to natural hazards, and how these differ within and across deltas;

Step VII. Evaluate how ecosystem services affect vulnerability and risk, and how ecosystem service indicators can contribute to improved risk management.

RQ3. What effective adaptation measures could be proposed when considering the role of ecosystem services to reduce vulnerability and risk in the future?

Paper 3: Ecosystem-based adaptation strategies to multi-hazard risk reduction and policy implications in the Pearl River and Yangtze River deltas, China (Peng et al., 2024b).

Step VIII. Compare the spatial distribution of vulnerability and disaster risk in the Pearl River and Yangtze River deltas using two risk assessment frameworks, and assess how different integrations of the multi-hazard risk components affected the risk profile;

Step IX. Determine key ecosystem services and ecosystem vulnerability indicators, and determine priority zones;

Step X. Provide available EbA options and policy suggestions on disaster risk reduction and climate change adaptation for two deltas.

The initial introduction chapter comprehensively reviewed and summarized the background of climate change, natural hazards, vulnerability and risk assessment, ecosystem service research, and studies related to global deltas. This chapter elucidates the theoretical and methodological basis and offered both theoretical and empirical motivations for the study. Chapter 2 (Paper 1) makes further adjustments to the existing risk assessment framework through the systematic incorporation of ecosystem service sub-component, and determined relevant ecosystem service types and indicators according to the environmental settings of deltas. Building on this, Chapter 3 (Paper 2) applies the newly developed risk assessment framework in China's Pearl River and Yangtze River delta regions, and maps out their vulnerability and risk profiles. Subsequently, Chapter 4 (Paper 3) presents EbA strategies and policy recommendations for the study sites, informed by further comparison and analysis of vulnerability and risk under two risk assessment frameworks, with a particular focus on the role of ecosystem services. Lastly, the conclusion chapter summarizes the theoretical and empirical contributions of each piece and the research as a whole, discusses possible limitations of the study, and provides recommendations for future research.

2. 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.

Keywords

Multiple natural hazards; Indicator-based approach; River deltas; Ecosystem vulnerability; Social vulnerability

2.1 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 7,000 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).

2.1.1 Vulnerability and risk assessment frameworks

As an established method in determining how SES are threatened by natural hazards, vulnerability and risk assessments have received 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 (Blaikie et al., 2014; Duncan et al., 2017; McElwee et al., 2017), 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, 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; Kuenzer et al., 2020).

Following the development of vulnerability and risk analysis theory, assessment models have also been developed. These mainly include the 'pressure and response model' (Blaikie et al., 2014; Kang et al., 2019), the 'exposure, sensitivity and adaptability framework' (Chang et al., 2021; Sano et al., 2015) and the integrated assessment of multi-hazard methods (Gallina et al., 2016). The pressure and release model argues that disasters result from the interaction of two pressures: the processes stemming from natural hazards and the vulnerability generated by these processes, viewing risk as a function of hazard and vulnerability (Risk = Hazard × Vulnerability), with a focus on regional-level analysis

(Wisner et al., 1994). The second type of framework combines three dimensions of exposure, sensitivity and adaptability to characterize vulnerability, aiming to capture multiple aspects of vulnerability and typically focusing on a single hazard. The third type of integrated assessment framework aims to explore the relationships between physical processes and social dimensions, emphasizing a comprehensive understanding of social-ecological vulnerability across different spatial scales. This approach 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.

2.1.2 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; Costanza et al., 2014; Mononen et al., 2016; Oteros-Rozas et al., 2014; Wang et al., 2014). 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.

2.1.3 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.

2.2 A proposed framework for deltas with the integration of ecosystem services

2.2.1 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. 2-1.

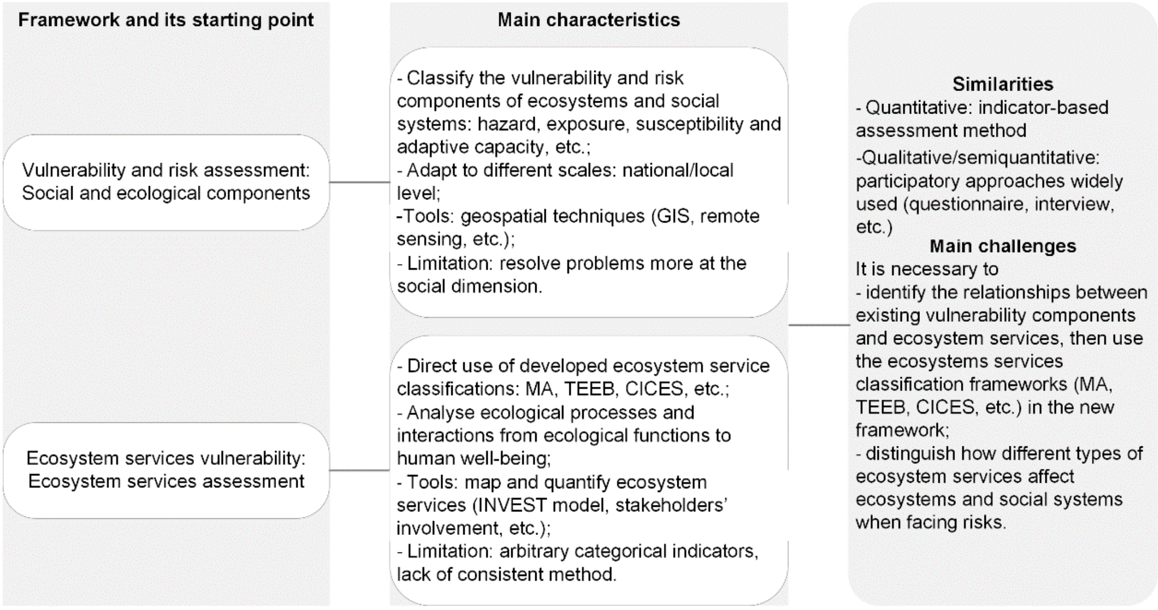

Figure 2-1 Assessment methods, main characteristics and challenges for vulnerability and risk analysis

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, 2014b). 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 inadequate for assessing and monitoring 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 (Asmus et al., 2019; Bevacqua et al., 2018). 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, 2018; 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 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.

2.2.2 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. The Delta-SES framework allowed clarifying risk components and provided an integrated view for risk assessments of SES. 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. 2-2) and the pre-existing Delta-SES framework is the inclusion of ecosystem services in the vulnerability component. This is an improvement from other frameworks and applications which had less consideration for the environmental dimension of risk (Sebesvari et al., 2016). 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, 2014b; Shah et al., 2020). Risk will be calculated as Hazard × Exposure × Vulnerability (IPCC, 2014b). In the process of vulnerability analysis and assessment, the ecosystem, ecosystem services and social system are divided into separated components, as shown in Fig. 2-2.

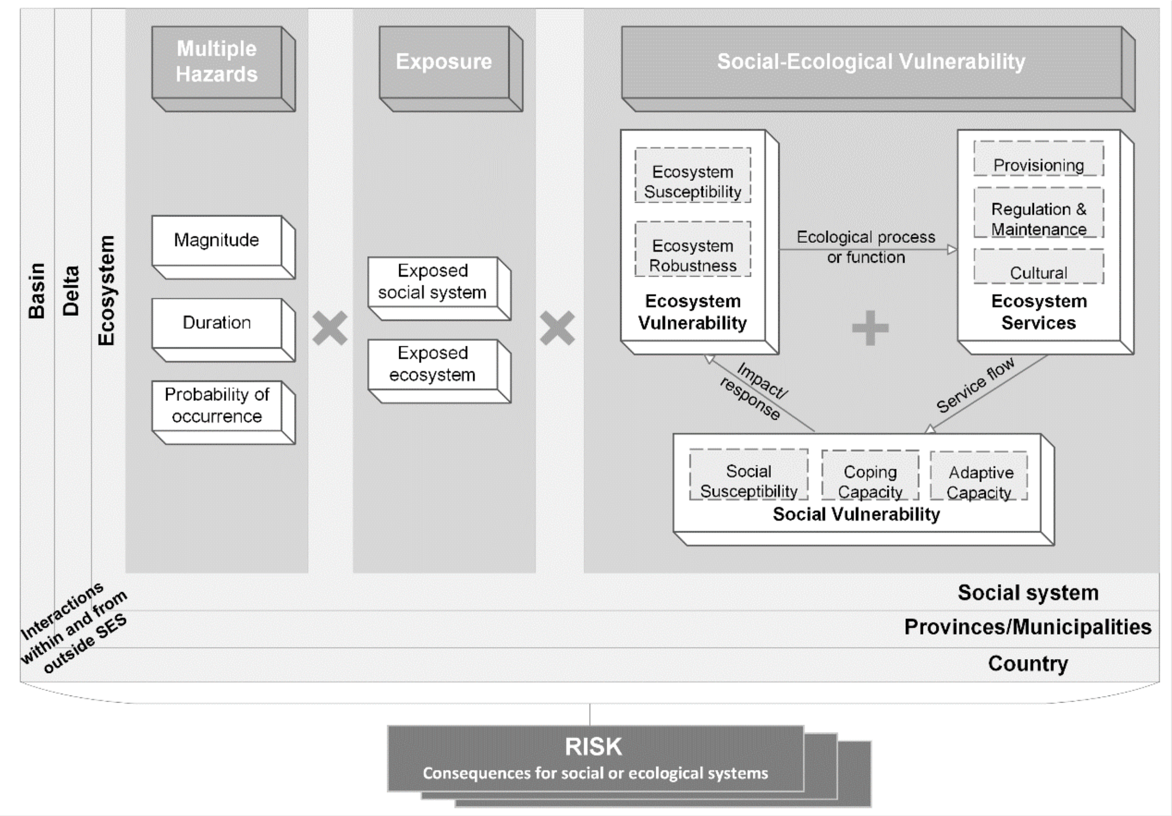

Figure 2-2 Conceptual framework for vulnerability and risk assessment of SES in deltas (Delta-ES-SES). Modified from Sebesvari et al. (2016) and IPCC (2014b); Shah et al. (2020).

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).

2.3 Ecosystem services in relation to vulnerability and risk assessments

2.3.1 Identifying ecosystem services relevant to risk assessments in deltaic and coastal areas

The 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, 2018). 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, 2018). 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 2-1.

Table 2-1 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** Ecosystem services	**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 (PUBYEAR > 1978))

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. 2-3). 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.

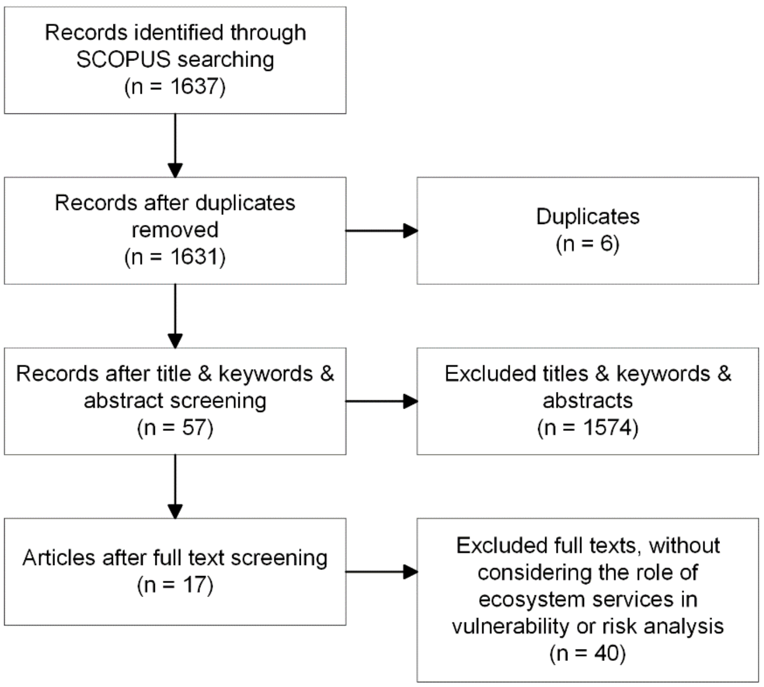

Figure 2-3 Summary diagram indicating the outputs of screening and exclusion processes of the recovered body of literature.

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 (Appendix 1). Table 2-2 shows the most important ecosystem services reported in reviewed papers, reflecting the primary ecosystem services considered in four main ecosystem types from the perspective of ecosystem service-related vulnerability. The ecosystem type classification could support illustrating ecosystem services and vulnerabilities in varying ecosystems and contexts, e.g. further risk analysis in the agricultural sector (agroecosystem) or wetlands (aquatic ecosystem). 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.

Table 2-2 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	√	√	√	√

2.3.2 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. 2-4). 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).

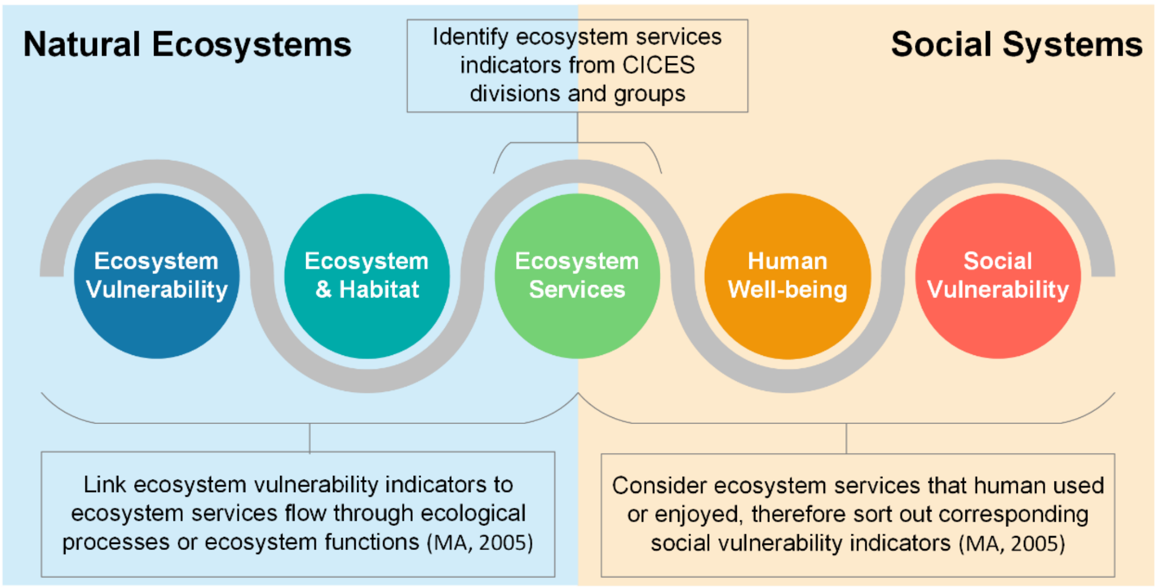

Figure 2-4 SES vulnerability cascade model modified from de Groot et al. (2010).

The application of the SES vulnerability cascade framework to establish the links between ecosystem services, ecosystem vulnerability and social vulnerability is presented in Fig. 2-

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.

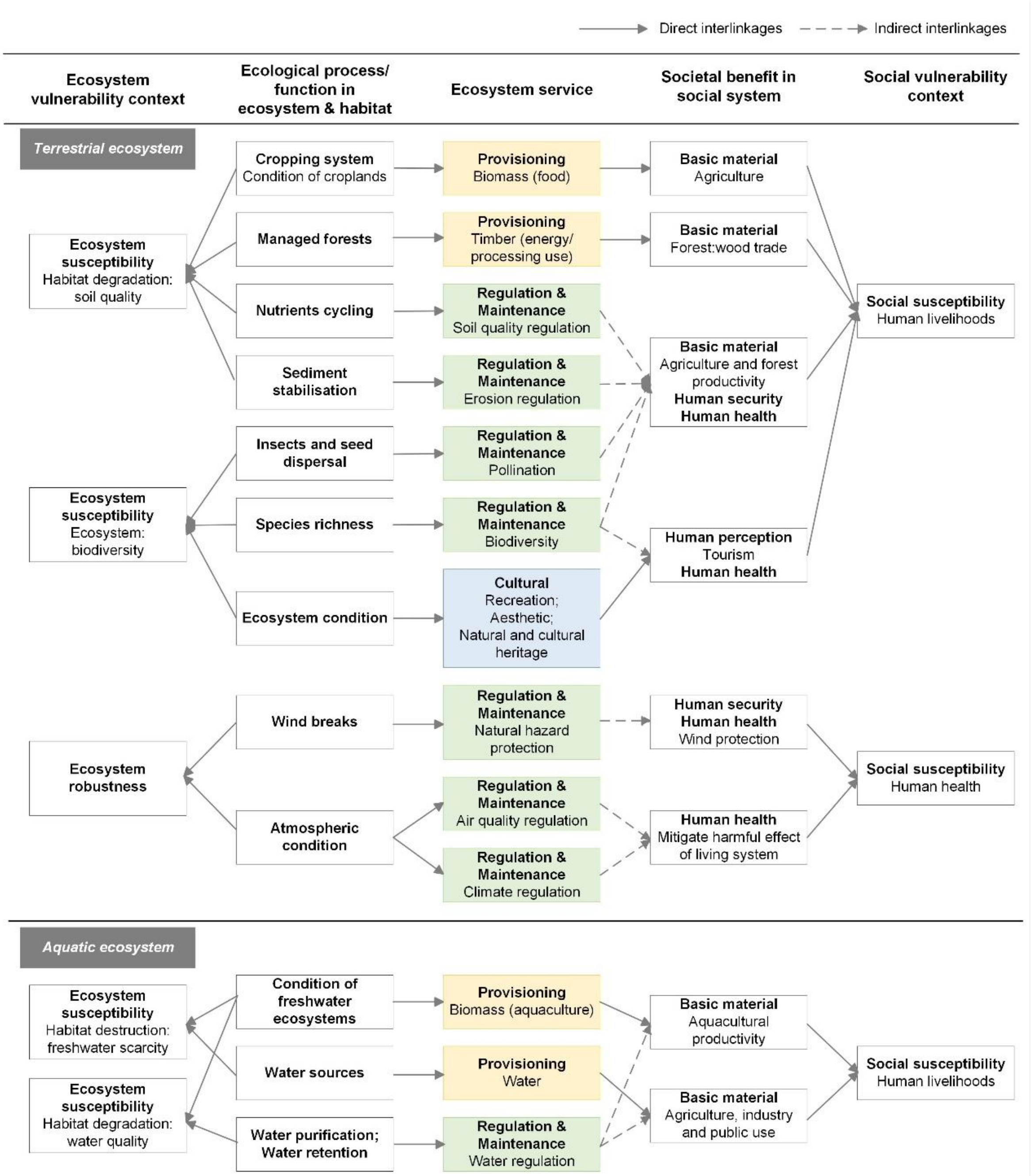

Figure 2-5 Schematic overview of the main interlinkages between ecosystem vulnerability, ecosystem services and social vulnerability. Among them, provisioning services, regulation & maintenance

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).

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 nitrogen 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 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, Appendix 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.

2.4 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 (Appendix 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. Appendix 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.

2.4.1 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 2-3 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.

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

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, 2018). 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, 2018). 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. Ideally, a higher level of ecosystem services would imply lower vulnerability. However, when selecting ecosystem service indicators in applications, certain obtained data (e.g., harvested production) primarily reflect human society's dependency on these services (social outcomes) rather than directly indicating the ecosystem's capacity to support human society. As a result, higher scores on these indicators may suggest higher vulnerability when exposed to certain hazards. These inconsistencies, arising from potential data availability issues, can be addressed through expert consultations and adjustments in later applications.

2.4.2 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 2-4. The ecosystem susceptibility to natural hazards shows the degree to which the ecosystems are adversely affected by climate change (IPCC, 2022a), 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 Appendix 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.

Table 2-4 Example indicators related to exposed ecosystem and ecosystem vulnerability identified from the literature review (see Appendix 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/%

Ecosystem robustness represents the capacity of ecosystems to stabilise 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).

2.4.3 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 2-5). A full list of indicators is provided in Appendix

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.

Table 2-5 Example indicators related to exposed social system and social vulnerability identified from the literature review (see Appendix 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 1,000 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)

Coping capacity is mainly divided into two components: individuals & households and infrastructure & services. These outline the ability of individuals and social systems to address, manage and overcome hazards and risks (IPCC, 2022a), such as the percentage of population without health insurance and existence of early warning systems. Adaptive capacity refers to the apparent scope to reduce adverse impacts and risks, which is assessed from the social background 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).

2.5 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 several potential benefits to improve risk assessment of deltaic SES, including providing a deeper understanding of the interactions between ecological and social processes, a more realistic assessment that considers the impacts of changes in ecosystem services on vulnerability and risk dynamics, and informed decision-making that promotes risk reduction. 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.

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, compounded by the complexity introduced by quantifying ecosystem services. 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 to try to develop some integrated or composed indicators to quantify ecosystem services as comprehensively as possible. Integrating interdisciplinary knowledge for these processes may also introduce uncertainties. 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.

3. Incorporating ecosystem services into comparative vulnerability and risk assessments in the Pearl River and Yangtze River deltas, China

Status: Published in Ocean & Coastal Management.

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Abstract

Coastal river deltas face high risks from multiple natural hazards due to the combined effects of human activities, natural processes, and climate change. Vulnerability and risk assessments are essential for reducing and managing risks and, in the process, contribute to sustainable development. Despite adopting a social-ecological and multi-hazard perspective, previous risk assessments failed to achieve balanced consideration of both social and ecological sub-systems. To address this gap, we used an integrated risk assessment framework which incorporates the role of ecosystem services (ES) as a core component. A modular indicator library of ES indicators relevant to coastal river deltas was used to characterize multi-risks in the Pearl and Yangtze River deltas. Results indicate a higher risk level in the Pearl River Delta, with the key drivers of vulnerability and risk varying with scales. Visualizing hazard-prone and highly vulnerable areas facilitates the implementation of targeted management measures and policies to reduce disaster risks from natural hazards. Ecosystem services have been identified as important factors of the risk profiles, and their inclusion in risk reduction strategies ensures that policies can be put in place that allow ecosystems to provide services sustainably to communities.

Keywords

Natural hazards; Social-ecological systems (SES); Indicator-based approach; Ecosystem services; Risk reduction and management; Analytic hierarchy process (AHP)

3.1 Introduction

Coastal river deltas are low-lying landforms shaped by sediment transport processes under the interaction of fluvial and marine dynamics (Anthony, 2015; Dalrymple and Choi, 2007). With abundant natural resource availability, deltas are of high economic and ecological importance on a global scale and have become important for agriculture, urbanization and other human activities (Syvitski et al., 2009). Therefore, deltas should be regarded as dynamically coupled social-ecological systems (SES) (Hoitink et al., 2020; Twilley et al., 2016; Zhang et al., 2022). The current evolution of deltas is affected by the combined effects of human activities, such as the construction of upstream dams and coastal dikes, river management decisions, and urban expansion. Meanwhile, these anthropogenic changes generate a series of environmental impacts, including sediment erosion, land subsidence, sea level rise, and increased vulnerability of SES to multiple natural hazards (Giosan et al., 2014; Nicholls and Cazenave, 2010; Syvitski et al., 2009).

The increase in recorded disasters from natural hazards during the past two decades compared to 1980-1999 was largely due to a significant increase in climate-related disasters, affecting over 4 billion people and causing nearly $2.97 trillion in global economic losses (CRED and UNDRR, 2020). Climate-related disasters increased by more than 82% from 3,656 in 1980-1990 to 6,681 in 2000-2019, with floods and storm surge events accounting for 70% of these (CRED and UNDRR, 2020). As hotspots of global climate change, combined with dynamic landscapes, high population density and intense pressure caused by human interventions, deltas are facing growing risks resulting from natural hazards such as hydrological (floods), meteorological (storms) and climatological (drought) events (Tessler et al., 2015). Reducing and managing risks as well as achieving sustainable development in deltas is a global challenge and aligns with the calls of the Sendai Framework for Disaster Risk Reduction 2015-2030 and the 2030 Agenda for Sustainable Development (17 Sustainable Development Goals, SDGs) (Brondizio et al., 2016a; Cremin et al., 2023).

Risk assessment aims to identify and characterize areas exposed and vulnerable to natural hazards and is an essential step in hazard prevention and mitigation (Anelli et al., 2022; Chen et al., 2021). This can simplify the risk management process at local, regional and national levels, not only facilitating the implementation of targeted risk mitigation measures to protect the existing environments but also supporting the development of long-term risk prevention strategies (Gallina et al., 2016; Sebesvari et al., 2016). Research has increased in recent years, focusing on using risk assessment to map how regional environments are threatened by multiple hazards, including socio-economic vulnerability analysis (Berrouet et al., 2019; Cutter et al., 2003; Kirby et al., 2019; Su et al., 2015; Yang et al., 2019), biophysical perspective on hazard formation and potential exposures (Dewan, 2013; Yang et al., 2015), and comprehensive assessments by capturing the coupled perspective of social and ecological system (SES) (Anderson et al., 2021; Chang et al., 2021; Depietri, 2020; Hagenlocher et al., 2018; Lozoya et al., 2015; Tessler et al., 2015).

While vulnerability and risk assessments have traditionally focused on the socioeconomic contexts when addressing vulnerability of social systems, natural hazard events also threaten human livelihoods and health by disrupting the supply of natural resources and the stability of ecosystems (Ng et al., 2019; Rangel-Buitrago et al., 2020). When natural hazards occur, all ecosystems in deltas and various ecosystem services are affected. In particular, the primary sector (represented by extractive activities such as agriculture, which is crucial for food production in delta regions), is extremely vulnerable to the direct impact of natural hazards (Brondizio et al., 2016a). Additionally, services such as soil quality, erosion control and climate regulation are linked not only to biomass production, but are also integral to coastal adaptation and risk reduction, such as coastal erosion management strategies (Gracia et al., 2018). Considering SES in risk assessments is therefore a new general trend (Brondizio et al., 2016b; Gracia et al., 2018). Reviews by Sebesvari et al. (2016) and Hagenlocher et al. (2019) both revealed that risk assessment studies predominantly focused on social dimensions of risk with inadequate consideration of ecological and environmental aspects, even in SES-based studies. To characterize better the inter-relationship of social and ecological systems, incorporating the concept of ecosystem services into risk assessment can help integrate the various components of the biophysical, ecological, social, and economic environments (Armatas et al., 2017; Collins et al., 2011; Peng et al., 2023).

The complex and interdependent characteristics of natural hazards mean it is impossible to address single risks in isolation (IPCC, 2022a; Nhamo et al., 2018). Risk assessments to single hazards fail to provide a comprehensive profile of the multiple risks stemming from various natural and anthropogenic forces (Gallina et al., 2016), which can materialise simultaneously or in a cascading pattern. Recognizing the diverse range of natural hazards and climate change impacts in deltaic environments underscores the necessity of assessing multiple risks and presenting a comprehensive multi-risk profile (Hagenlocher et al., 2018; Tessler et al., 2015). Consequently, adopting a multi-hazard risk perspective that accounts for the spatial scales of multiple hazards is crucial in devising efficient risk reduction and adaptation strategies (IPCC, 2022a).

As a coastal nation whose landmass covers a large geographic range, multiple climatic regions and ecotypes, China is severely affected by numerous environmental disasters. The country is ranked among the top ten countries globally most affected by natural hazard-related disasters over the period from 2000 to 2019, in terms of hazardous event occurrences, economic losses, and human casualties, as shown by data from the Emergency Events Database (EM-DAT) (CRED and UNDRR, 2020). Notably, southern China (Pearl River Delta) and eastern China (Yangtze River Delta) have experienced a particularly high incidence of flooding events (Kundzewicz et al., 2019). Therefore, flood risk analysis for the Yangtze or Pearl River Delta and even China as a whole has received the most attention and included studies focusing on model-based flood hazard assessment and prediction (Fang et al., 2020; Lin et al., 2020; Xu et al., 2014; Yin et al., 2020; Zhang et al., 2014; Zhao et al., 2021), and vulnerability and risk assessments of flooding (Chen et al., 2021; Jian et al., 2021; Sun et al., 2022; Yang et al., 2015). In addition, there are vulnerability or risk assessments for other single hazards, encompassing cyclones (Sajjad et al., 2020; Yin et al., 2013; Zhang et al., 2017; Zhou et al., 2021), storm surges (Li and Li, 2011; Lilai et al., 2016; Xianwu et al., 2020), drought (Chen et al., 2016), and pollution (Liang et al., 2022; Zhu et al., 2019). Previous studies of risk assessments in China also lacked an SES perspective, either emphasising or exclusively considering social vulnerability (Ge et al., 2017, 2013; Sun et al., 2019; Yang et al., 2019; Yu et al., 2018). Currently, there is inadequate documentation of integrated vulnerability and risk assessments to multi-hazards in these two deltas. In the Yangtze River Delta, Liu et al. (2013) mapped the exceedance probability distribution of typhoons and flood hazards to human casualties. In another research, the Global Delta Risk Index was computed to better identify green infrastructure prioritization in part of the

Yangtze River Delta (Ou et al., 2022). The research predominantly focused on green infrastructure, and lacked the inclusion of hazard magnitude and local knowledge to determine diverse dimensions of SES vulnerability, particularly those hazard-dependent indicators. Consequently, multi-hazard risk assessments are needed, encompassing not only the whole Pearl and Yangtze River deltas but also an exploration of regional disparities across both of these deltaic environments.

Addressing the above-mentioned gaps, we developed a multi-hazard risk index for deltas from an integrated perspective of human, economic, and environmental dimensions through a conceptual framework and modular indicator-based tools. This study involved the systematic integration of ecosystem services to address the inter-relation between social and ecological systems, using a combination of quantitative and qualitative approaches to describe coupled SES dynamics for deltas. The application of the new framework aims to assess the vulnerability and risks to multiple hazards in the Pearl River Delta and Yangtze River Delta, and to understand their regional differences. In this paper we (1) determine the overall vulnerability and risk profile of the Pearl and Yangtze River deltas; (2) assess which regions in these deltas are at higher risk levels to natural hazards, and how these differ within and across deltas; and (3) we evaluate how ecosystem services affect vulnerability and risk, and how ecosystem service indicators can contribute to improved risk management.

3.2 Materials and methods

3.2.1 Study areas

The Pearl River Delta (PRD) has a total land area of 55,000 km^2 and a population of 64 million, which is only located in Guangdong Province (Fig. 3-1) (PSB, 2019). The population density of the delta is 1172 persons/km^2, which is significantly higher than both China’s average, and that of the Yangtze River Delta (YRD) (Table 3-1). It has become the world's largest metropolitan area in both size and population (The World Bank, 2015). From July to September, an annual average of 7 to 9 typhoons land in the eastern and southern coastal areas of China (CMA, 2014). From 2011 to 2020, the average direct loss from storm surges in the PRD alone was as high as US$433.5 million per year, exceeding the YRD

(MNR, 2021). Besides, the PRD region is identified as a significant risk hotspot to tropical cyclones (typhoons), requiring the implementation of urgent risk reduction and management strategies (Sajjad et al., 2020).

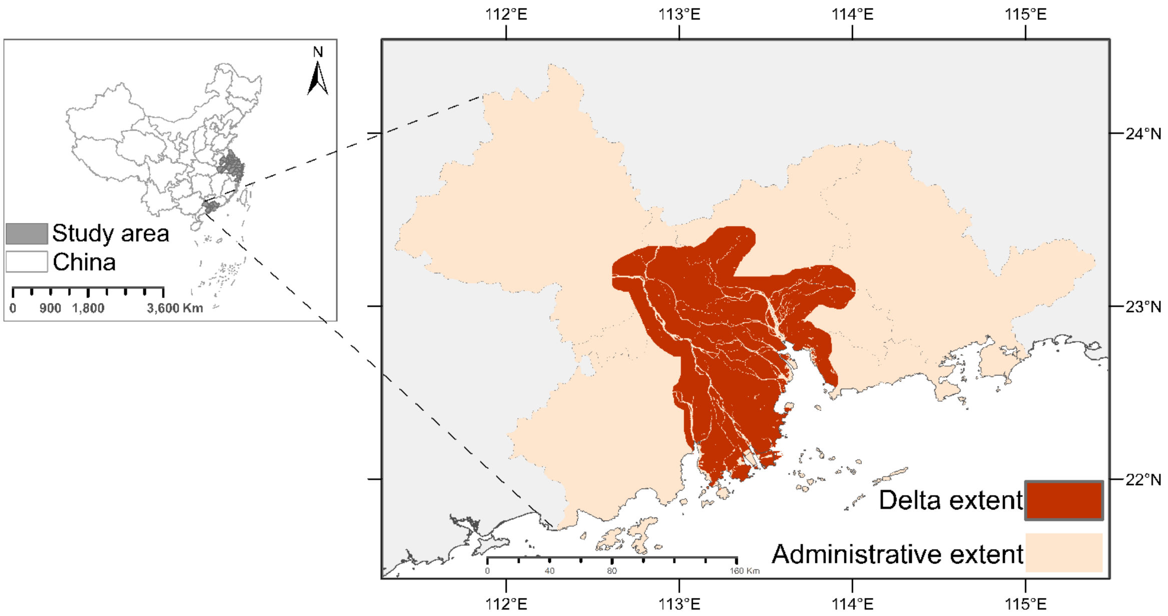


Figure 3-1 Map of Pearl River Delta. The administrative tracts are marked in yellow and represent the study areas. Data from GADM (2018). Red areas show the extent of the delta (data from Tessler et al. (2015), based on geographical characteristics and remote sensing images).

Table 3-1 Comparison of biophysical and social characteristics between China, PRD and YRD. Source: NBS (2020).

		China	PRD	YRD
Biophysical	Land area (km^2)	9.6 million	55,000 (0.6% of China's total land area)	225,000 (2.3% of China's total land area)
	Climate	Diverse climate due to its vast territory	Subtropical monsoon climate with abundant rainfall and high humidity	
Social	Population (million)	1,400	64 (4.6% of China's total population)	136 (9.7% of China's total population)
	Population density (person/km^2)	148	1172	750
	GDP (billion US$)	14,306	1,258 (8.8% of China's total GDP)	2,952 (20.6% of China's total GDP)

The YRD is a relatively developed economic region in the eastern coastal areas of China (Fig. 3-2). This study adopts the definition of the core region in the Outline of the Yangtze River Delta Regional Integrated Development Plan, consisting of Shanghai, 9 cities in

Jiangsu Province, 9 cities in Zhejiang Province and 8 cities in Anhui Province, with an area of 225,000 km^2 (The CPC Central Committee and General Office of the State Council, 2019). The city cluster, led by Shanghai, has been recognized as one of the six major urban belts in the world (NBS, 2004). As an agricultural and industrial centre, the Yangtze River Delta comprises 2.3% of the area and about 9.7% of the population of China; as of 2019, the region has generated nearly 20.6% of China's total Gross Domestic Product (GDP) (Table 3-1). The Yangtze River Delta is vulnerable to multiple natural hazards such as typhoons, flooding, and storm surges due to its geographical location (Ge et al., 2013). According to the Bulletin of China Marine Disaster (MNR, 2021), the average direct economic loss from 2011 to 2020 caused by storm surges is about US$297.7 million per year.

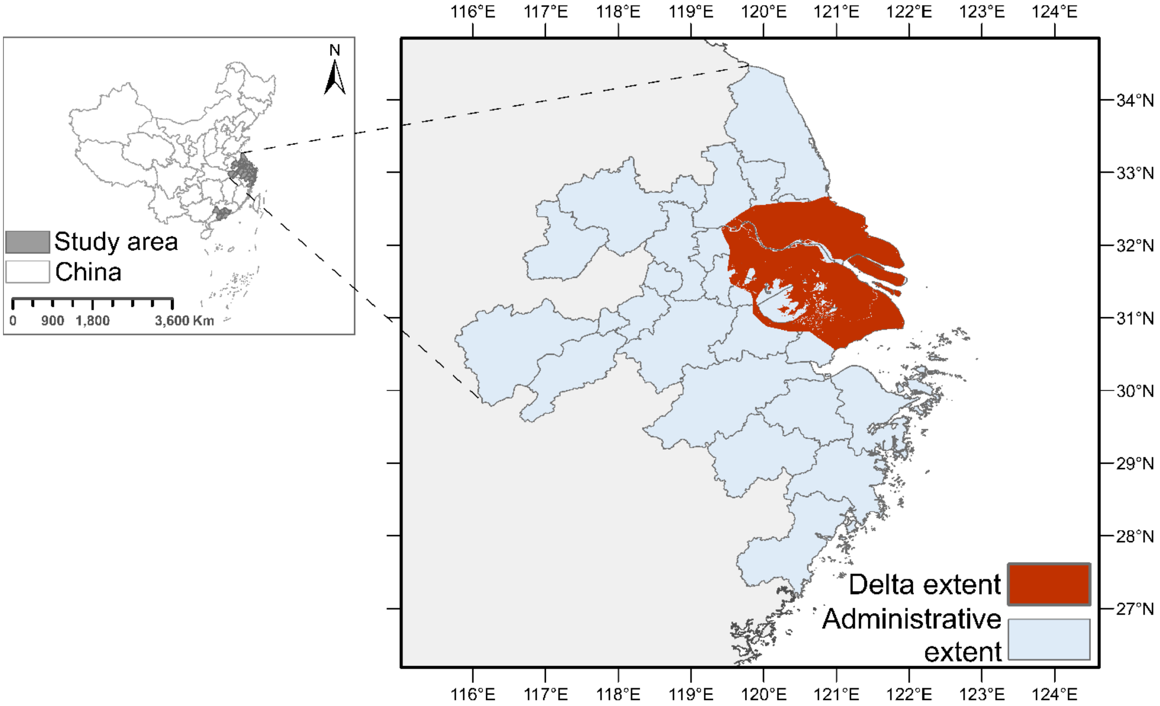


Figure 3-2 Map of Yangtze River Delta. The administrative tracts are marked in blue and represent the study areas. Data from GADM (2018)*. Red areas show the extent of the delta (data from* Tessler et al. (2015)*, based on geographical characteristics and remote sensing images).*

Managing the risks faced by the delta regions with their distinct demographic and economic disparities from the rest of China is critical to achieving sustainable development. Furthermore, understanding the regional risk differences between the PRD and YRD helps to identify the key drivers causing the final multi-risk, then formulating goal-oriented adaptation and risk reduction measures.

3.2.2 Research design

3.2.2.1 Risk framework

This study applies a comprehensive research framework (Delta-ES-SES) for deltaic SES vulnerability and risk assessment (Peng et al., 2023, also Chapter 2), which was adapted from Sebesvari et al. (2016). The adapted framework integrates various risk components (Risk = Hazard × Exposure × Vulnerability) from the spatial perspective of the SES and can be applied to single and multiple hazards (Fig. 3-3). This modular structure establishes the linkage between ecosystem services and vulnerability, taking into account the social, ecosystem, and ecosystem service dimensions of vulnerability. The indicator-based methodology linked to different levels of the indicator library can be easily adjusted for different research priorities and assigning weights, which is applicable to the characteristics of delta environments and enables intra-delta and cross-delta comparisons.

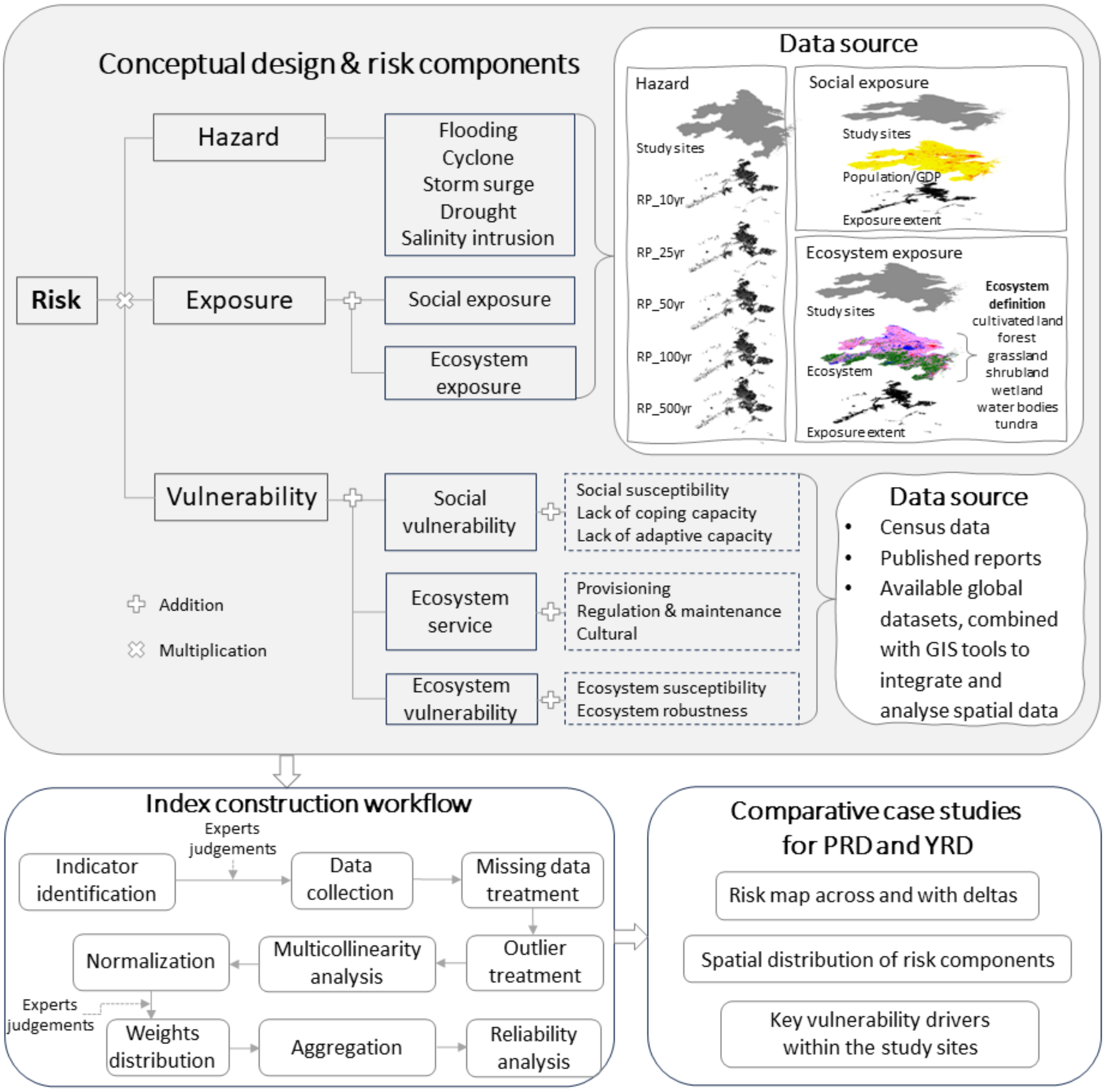


Figure 3-3 Schematic conceptual and methodological structure of the Delta-ES-SES risk framework. The data source for hazard and exposure (the upper right) mainly shows the data acquisition process taking the flooding in the Yangtze River Delta as an example. RP_10yr to RP_500yr refer to different return period maps of floods. Detailed information for each indicator is included in Appendix 6.

3.2.2.2 Risk components and data collection

Focusing on differences in disaster risk levels across deltas, we used datasets at various scales representing multiple factors contributing to the vulnerability and risk profile of deltas for further analysis and integration. Considering data availability, we assessed the multi-hazard risks by administrative unit (city-level). The Delta-ES-SES framework classifies risk into hazard, exposure and vulnerability components, with additional sub-components. It also allows calculating and comparing single hazard risk and identifying the main drivers of final risk scores. Appendix 6 provides an overview of the detailed information and data processing steps of indicators for each component that can be used to support future studies.

Hazard and exposure

This study mainly considers four types of natural hazards (IFRC, 2022): (1) Hydrological (flooding), (2) Meteorological (cyclones and storm surges), (3) Climatological (drought) and (4) Mixed (salinity intrusion). The selection criteria of hazard indicators (flooding, cyclone, storm surges, and salinity) are spatial data that can be mapped in a GIS environment (tool: Arc-GIS version 10.8), using a wide variety of data sources from international organizations and publishing papers (Table 3-2). As for drought, based on the precipitation and potential evapotranspiration data provided by the CCCS (2021) dataset from 1979 to 2020, spatially explicit data of drought score and frequency were developed for the study area by the Standardized Precipitation Evapotranspiration Index (SPEI) construction method introduced by Vicente-Serrano et al. (2010). Social exposure consists of the percentage of people and economics (GDP) exposed to these hazards, and ecosystem exposure is defined as the percentage of ecosystem area exposed to hazard, as Fig. 3-3 shows. These data are derived from the combination of hazard data and spatial data on population, economics and Land Use / Land Cover (LULC), respectively, resulting in the mean value for each administrative area.

Table 3-2 Indicators, data type and sources used for hazard and exposure components.

Category	Indicator	Time Period	Data Source
Hazard			
Flooding	Mean water depth (in m)	Return period: 10, 20, 50, 100, 500 years	Francesco et al. (2016)
Cyclone	Wind speed (km/h) Cyclone frequency	1970 - 2009	Peduzzi (2014)
Storm surge	Sea levels (in m)	Return period: 10, 25, 50, 100, 250, 500, 1000 years	Muis et al. (2016)
Drought	Standardized precipitation evapotranspiration index (SPEI)	1979-2020	Vicente-Serrano et al. (2010)
Salinity intrusion	Salinity (total dissolved solids; mg/l)	1979-2010	van Vliet et al. (2021)
Exposure			
Social Exposure	% of population exposed to each hazard	2020	WorldPop (2018)
	% of economics exposed to each hazard	2019	Xinliang (2017)
Ecosystem Exposure	Ecosystem exposed to each hazard (%)	2020	NGCC (2020)

Vulnerability

In this study, vulnerability is composed of (1) social vulnerability (social susceptibility, lack of coping and adaptive capacities), (2) ecosystem services (provisioning, regulation & maintenance, and cultural services), and (3) ecosystem vulnerability (ecosystem susceptibility and ecosystem robustness). A list of indicators was obtained by combining a systematic review of the deltaic SES-related ecosystem services literature and risk assessment papers (Peng et al., 2023, also Chapter 2), then identifing a series of hazard and vulnerability indicators for the YRD and PRD by inviting experts to fill out indicator questionnaires. Forty-two questionnaires were obtained from experts belonging to relevant academic institutions or government sectors in China, with knowledge of ecosystem conservation and restoration, ecology, climate change adaptation, land management and other related backgrounds. Vulnerability to different types of hazards could be different and can change over time (Gallina et al., 2016). Expert consultation not only distinguishes the directional effects of each vulnerability indicator with the hazard (increasing +/decreasing - vulnerability), but also adjusts the indicator for the study area. Data sources and time periods of indicator data availability vary, and are mainly obtained from census data, available global databases, as well as data from some published papers. The indicators "Forest Connectivity" and "Wetland Connectivity" are calculated from existing databases and GIS plugin (Saura and Torné, 2009). Finally, vulnerability is composed of 46% social vulnerability and 54% ecological (ecosystem service and ecosystem) indicators. Section 2.2.2.4 provides a specific list of vulnerability indicators and their associated weights, and Appendix 6 provides information on data sources. Further information related to the consulted experts is provided in Appendix 7.

Various indicators related to social vulnerability are determined from expert consultation to present the overall status of the social system under the context of vulnerability and risk assessment. This research divides indicators into three categories, namely indicators related to social susceptibility (11 indicators) and lack of coping (12 indicators) and adaptive capacity (3 indicators). Social vulnerability indicators are generally available through census data in China. Social susceptibility includes indicators related to key services (e.g. indicators 'access to irrigation') and economic and demographic characteristics, such as the indicator 'dependency ratio'. Coping capacity reflects the ability of humans to address and overcome the adverse impacts of hazards (IPCC, 2022a), which is mainly divided into two aspects: individual & household and infrastructure & services. Adaptive capacity refers to the ability to reduce adverse risks and impacts, which is assessed by aspects of social and governmental management.

Ecosystem service indicators related to vulnerability are divided into provisioning (6 indicators), regulation & maintenance (12 indicators) and cultural services (3 indicators). Provisioning services, include indicators related to agricultural, forestry and aquaculture production and water resources, and jointly determine the ecosystem's ability to provide various materials or energy (Haines-Young and Potschin, 2018). Regulation and maintenance services mainly reflect beneficial effects on the human environment through biochemical or physical processes (Haines-Young and Potschin, 2018). This research considers soil quality regulation, erosion regulation, pollination, biodiversity, natural hazard protection, air quality regulation, climate regulation and water regulation. Indicators for cultural services are related to human habitation of landscapes and environments, and include the development of tourism and accessible recreation areas.

The ecosystem susceptibility to natural hazards indicates the propensity of the ecosystems to be adversely affected (IPCC, 2022a). Ecosystem susceptibility indicators are divided into habitat destruction (3 indicators: percentage of deforested area, percentage of wetland loss, and percentage of area covered by problem soils), habitat degradation (2 indicators: increased use of chemicals and fertilisers, Normalized Difference Vegetation Index) and habitat fragmentation (3 indicators: forest connectivity, wetland connectivity and river connectivity). Ecosystem robustness shows the ability of ecosystems to stabilise various ecological functions and respond to risks (Sebesvari et al., 2016), and includes two indicators: percentage of area of nature reserves and funding on environmental protection.

3.2.2.3 Data processing

The computed risk index supports a spatial analysis workflow. However, as there were no available spatial data for some indicators, this study mapped the risk at the administrative scale. For spatial datasets, statistical values (mean) for administrative areas were derived using the zonal tool in ArcGIS 10.8. As shown in Fig. 3-3, data processing included missing value analysis (mean values of surrounding areas) and outlier treatment, as detailed in Appendix 7. Box plots were computed to detect the outliers of all data, where outliers were defined as data points that were located outside the whiskers of the box plot 1.5 * interquartile range. A winsorization or trimmed estimators approach was used to process the potential outliers after checking the data sources. The second step was to check for multicollinearity within each indicator domain. The Correlation Coefficient Kendall's tau_b was used in this analytical procedure (with Kendall's tau_b > 0.9 indicating collinearity) (Hagenlocher et al., 2018). After taking into account the data features and the aim of the composite indicator (Nardo et al., 2005), the rescaling (min-max normalization) method was applied to redistribute all indicators to a range with an average of zero and a standard deviation of one. Some indicator data were adjusted so that all high indicator values indicate high vulnerability and risk.

3.2.2.4 Aggregation method

This study weighted the risk components using a combination of empirical evidence and the analytic hierarchy process (AHP and improved AHP). The AHP has been widely used in risk assessments to identify the relative importance of various associated indicators (Ouma and Tateishi, 2014; Pathan et al., 2022), which enables a better understanding of local environments (Ishizaka and Labib, 2011). Regardless of the delta environment settings, the drivers contributing to risks and final risk scores will be region-specific (Pathan et al., 2022). Given the geographic attributes of vulnerability and risk, a combination of stakeholder and scientific knowledge may improve risk assessment and disaster management (Morelli et al., 2021). Based on literature analysis and IPCC reports (2014a), the risk components (hazard, exposure, and vulnerability) are calculated based on equal-weighted standardization. For the exposure and vulnerability subcomponents (indicators ≤3, see Fig. 3-3), we took the traditional AHP approach to develop pairwise comparison matrices for each component. Consistency ratios less than 0.10 are acceptable (Saaty, 2008). This standard AHP requires pairwise comparison, which is unsuited to multi-indicator research, especially if there are more than 10 elements. It is time-consuming and may lead to inconsistent judgments. An improved AHP (IAHP) is therefore adopted to weigh the criteria of all vulnerability sub-components (within ecosystem vulnerability, ecosystem service and social vulnerability), which is to change the pairwise comparison to the ranking of the elements (Fengwei et al., 2013). The main step is to rank the indicators according to expert consultation. The most important indicator is assigned a value of 10, the least important is 1, and the values of other indicators are assigned values through linear interpolation based on the importance order. The other steps are the same as in standard AHP, calculating an eigenvector according to the comparison matrix, which is the final weight distribution. Fig. 3-4 presents the final distribution of weights in this study.

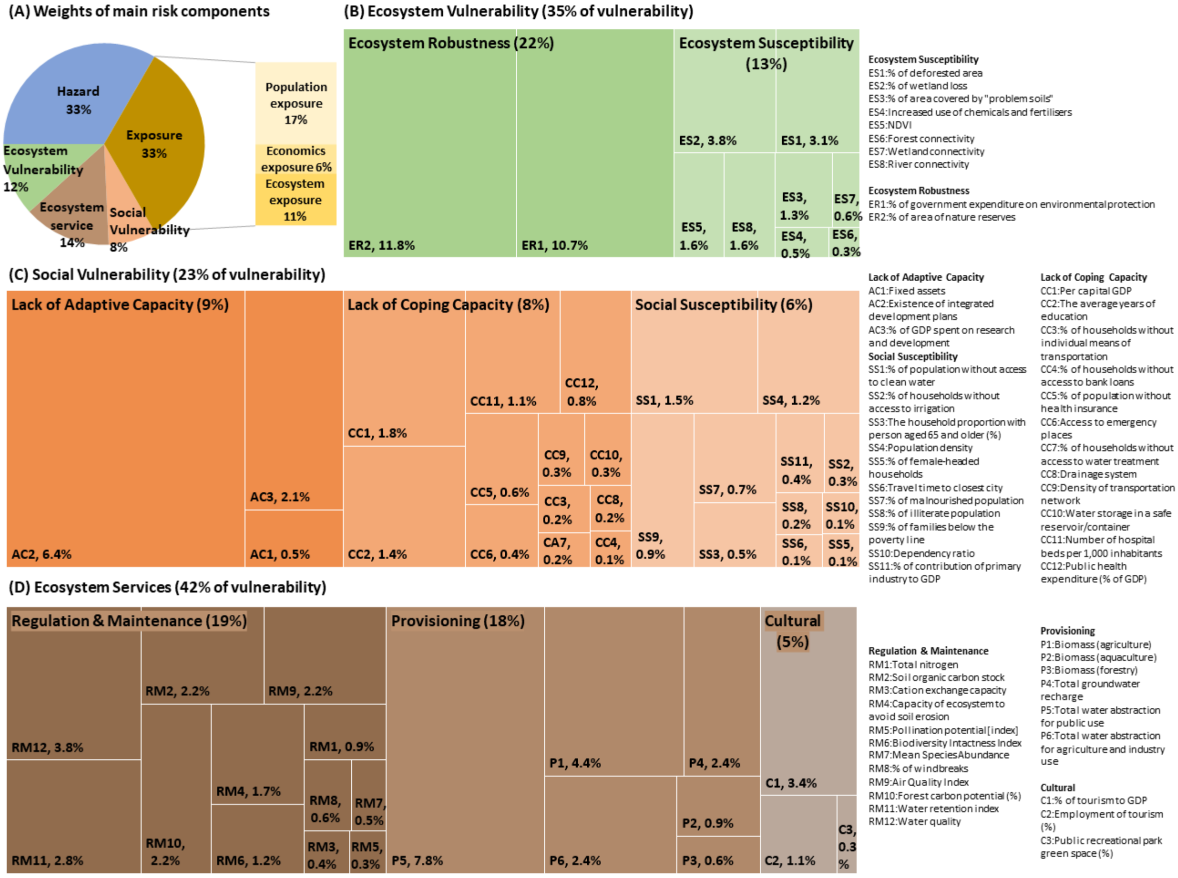


Figure 3-4 Final distribution of weights across risk domains. (A) Hazard, Exposure, Vulnerability: equal weights (33%); Exposure and Vulnerability sub-components: AHP method; (B), (C), and (D) Weight assignment for sub-components (AHP method) and each vulnerability indicator (IAHP method). The percentages displayed in these three figures pertain to the vulnerability component.

Finally, following the modular framework, the (multi-)hazard, exposure and vulnerability of the deltaic SES are aggregated by multiplicative aggregation into a (multi-hazard) risk index, that is,

$$RISK_{SES} = HAZ_{SES} * EXP_{SES} * VUL_{SES}$$

Where HAZ_{SES} is the hazard score; EXP_{SES} is the exposure score, which is calculated as

$$EXP_{SES} = \sum_{i=1}^{n} (w_i * EC_{SES})$$

Here EC_{SES} is the different exposure component of SES where w_i is the weight of each type of exposure indicator.

Besides, VUL_{SES} is the vulnerability score of SES, which use the mean of three vulnerability domains (after combining the weights w_j), which is calculated using

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

VD_{SES} refers to ecosystem vulnerability, ecosystem services, and social vulnerability, which is calculated using

$$VD_{SES} = \sum_{s=1}^{n} (w_s * VD_s)$$

where w_s is the weights of indicators in the sub-component of vulnerability domain (VD) (e.g. indicators of ecosystem susceptibility and robustness). Here VD is calculated by the aggregation of each normalized indicator (x_k') with specific weights (w_k).

$$VD = \sum_{k=1}^{n} (w_k * x_k')$$

Final outputs are visualized using ArcGIS 10.8 based on manual equal interval across deltas and quantile classification within the delta, respectively. Equal interval classification emphasizes the number of risk scores relative to other scores, which visualizes the absolute distribution of risk values for all regions of the two deltas, allowing identification of regions with highest/lowest and closest distribution of risk scores. Meanwhile, the quantile classification assigns equal number of administrative units to each class, which could interpret the spatial patterns of relative risk scores within the delta.

3.2.2.5 Reliability analysis

We applied the reliability index to examine the data quality used in this study, which is adjusted and developed by Hagenlocher et al. (2018) and Marin-Ferrer et al. (2017). It involves (1) percentage of missing data and outliers for vulnerability indicators, including any that have been estimated; (2) percentage of missing hazard data; (3) percentage of proxy indicators; and (4) percentage of indicator data at provincial level rather than city level. The final reliability index ranges from 0 to 100%, and the larger the number, the higher the reliability. Based on this approach, the reliability indices for the PRD and YRD are 83% and 82%, respectively, and details are provided in Appendix 7.

3.3 Results

3.3.1 Multi-hazard risk of deltaic social-ecological systems

Using the Delta-ES-SES framework, we present the risk profiles from the multi-hazard risk assessment across the two coastal river deltas, with risk scores ranging from 0.028 to 0.183 (Fig. 3-5). About 42% of the 36 administrative tracts in the study area are at medium to high risk levels (risk score > 0.08). Fig. 3-5B and 3-5C show relative multi-hazard risk scores within the deltas, which are 0.059 – 0.163 for the PRD region and 0.028 – 0.183 for the YRD region. It can be seen from the data in Fig. 3-6 that the average risk to SES in the PRD (risk score 0.099) is higher than the YRD (risk score 0.071), and its hazard exposure is also higher than the average scores in the YRD. Compared to the YRD, all cities in the PRD are at medium to high risk.

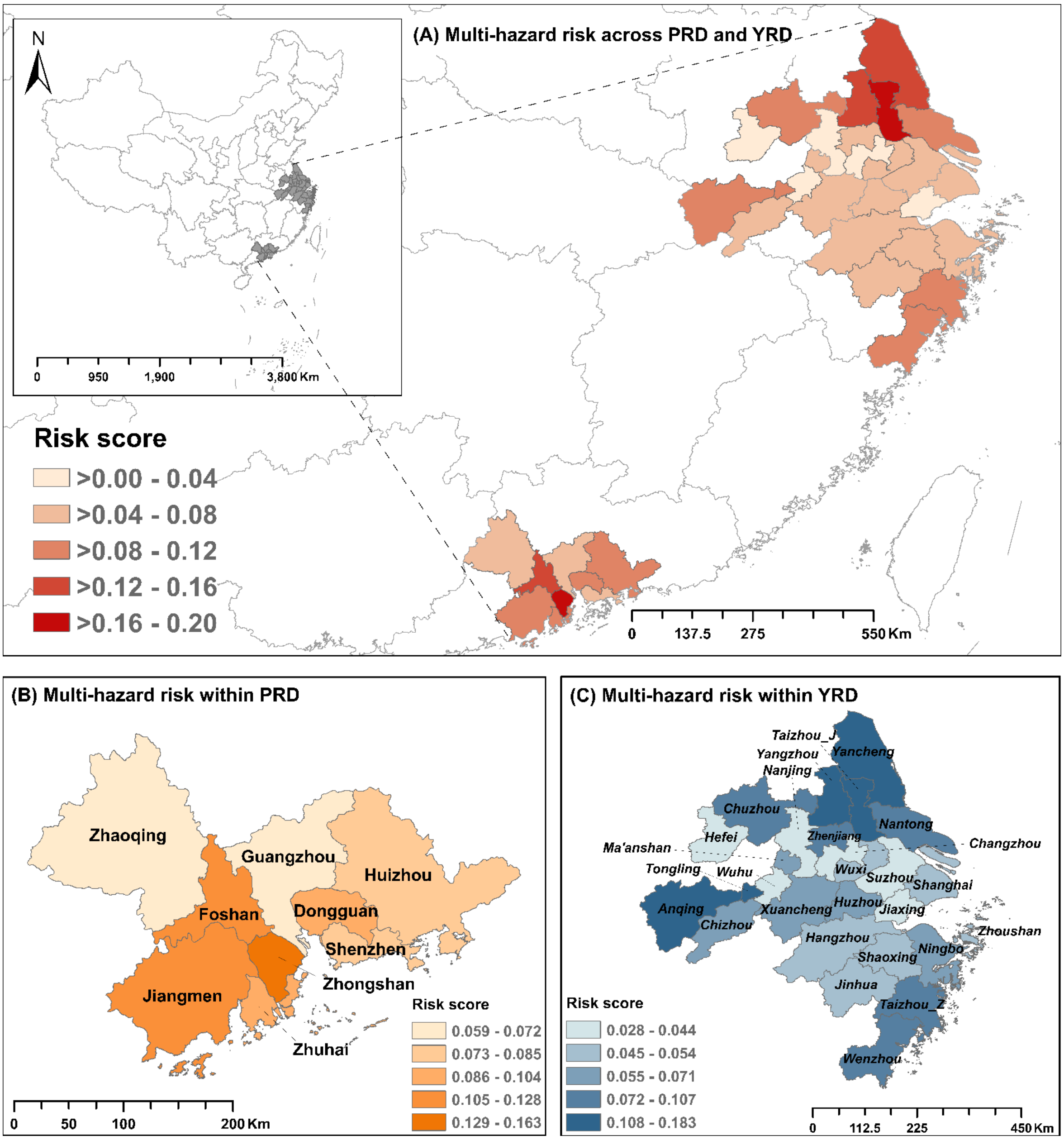


Figure 3-5(A) Multi-hazard risk across the deltas (risk score classification: equal interval); (B) and (C) Multi-hazard risk within the Pearl River Delta and Yangtze River Delta, respectively (risk score classification: quantile method). Note: Risk score ranges from 0 to 1, with higher scores indicating higher risk levels. The colours in (B) and (C) are not comparable, specific values are provided in the corresponding legends. The visualization of risk score can vary depending on the classification method used.

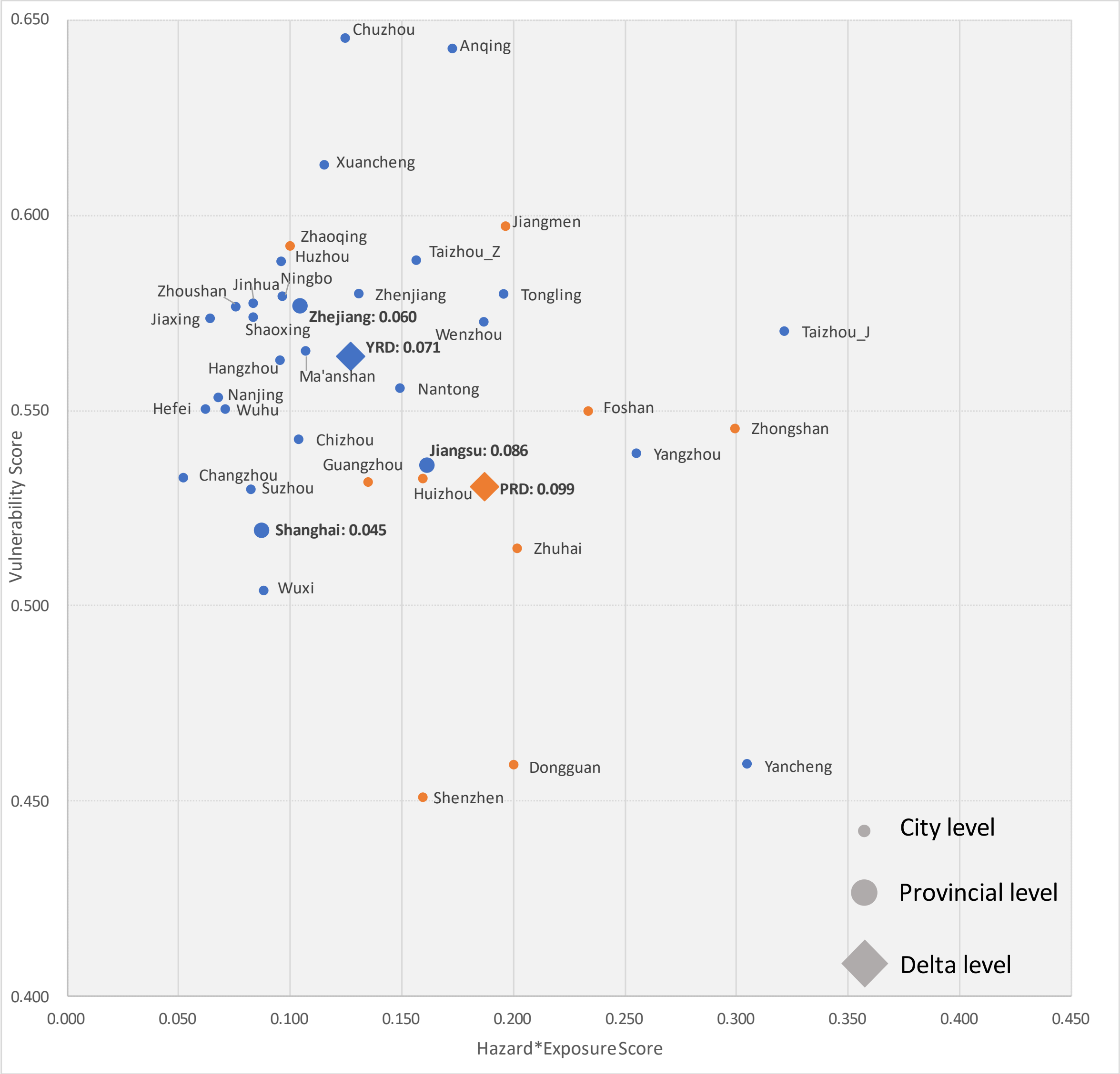


*Figure 3-6 Scatter plot of risk assessment results, showing the proxy indices for hazard*exposure and vulnerability used to estimate the risk indices, blue colour for Yangtze River Delta (YRD) tracts and orange colour for Pearl River Delta (PRD) tracts. Hazard*Exposure refers to the multiplication of hazard and exposure scores. Higher vulnerability scores indicate higher vulnerability levels, and the scores for all cities ranged between 0.45 and 0.65. Dot size represents different administrative units: city level, provincial level, and delta level. Taizhou_J and Taizhou_Z represent Taizhou in Jiangsu Province and Taizhou in Zhejiang Province, respectively.*

High-risk cities are led by high hazard exposure and moderate to high vulnerability, including two cities with the highest risks: Taizhou_J (risk score 0.183) in the YRD and Zhongshan (risk score 0.163) in the PRD. Most cities in the PRD are characterized by moderate to high vulnerability and moderate to high hazard exposure (orange dots in Fig. 3-6), except for Zhaoqing and Guangzhou. These two cities have lower multi-hazard exposure, which are located in the interior of the PRD, as shown in Fig. 3-5(B). The risk levels of YRD show large variability, as it is shared by four adjacent provinces (blue dots in medium size), with Jiangsu (risk score 0.086) having significantly higher average risk than Anhui (risk score 0.071), Zhejiang (risk score 0.060), and Shanghai (risk score 0.045). Low-risk cities have lower hazard exposure scores, are mainly located in central inland areas of the YRD, as shown in Fig. 3-5(C). Generally, cities with higher risk scores are mostly located in the northern and southern coastal areas, with moderate to high distribution of exposure to hazardous events. There are some exceptions, like Tongling and Anqing, which are in the interior of the YRD, and which have moderate to high risk levels. In order to understand the risk differences and their internal drivers across the study area, the risk components of the deltas are visualized separately (Fig. 3-7).

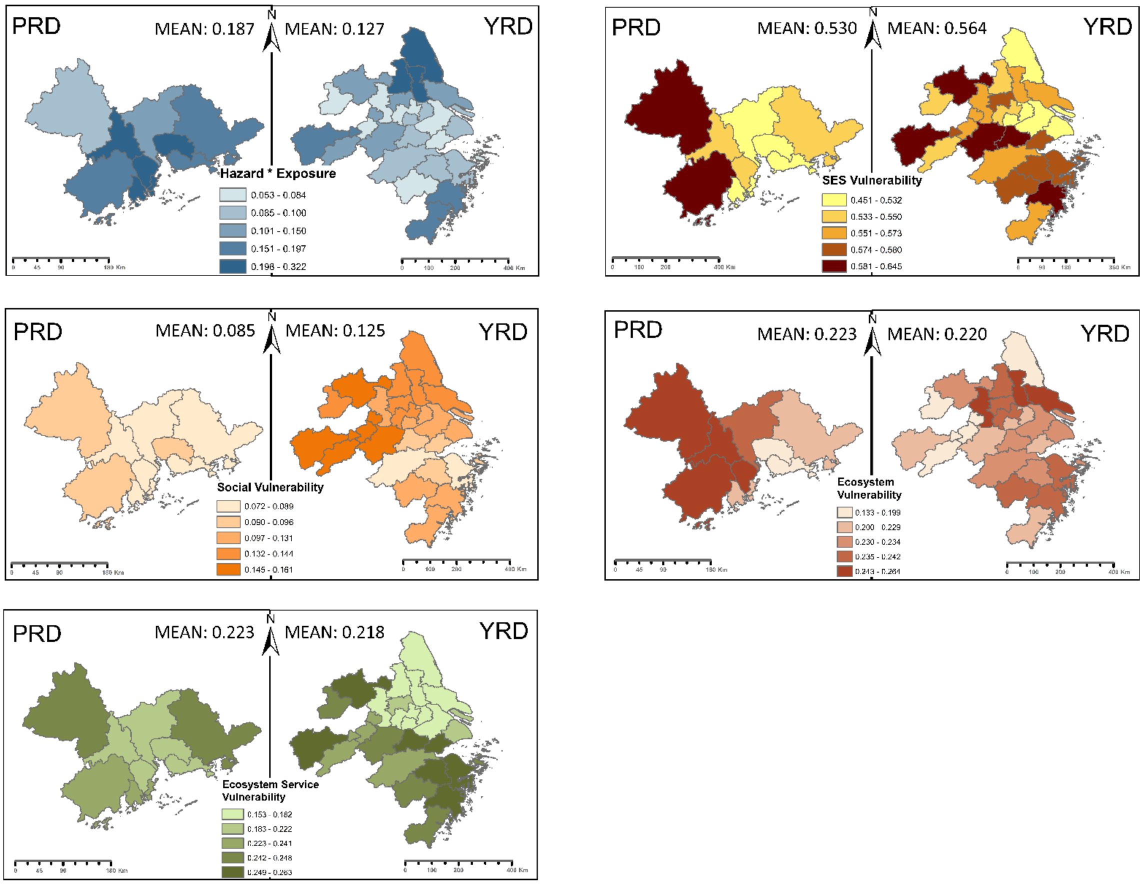


*Figure 3-7 SES Hazard*Exposure, SES Vulnerability, and corresponding scores of vulnerability domains for multi-hazards: Social vulnerability, Ecosystem vulnerability and Ecosystem service vulnerability. Score ranges are based on quantile classification. SES Hazard*Exposure refers to the multiplication of hazard and exposure scores.*

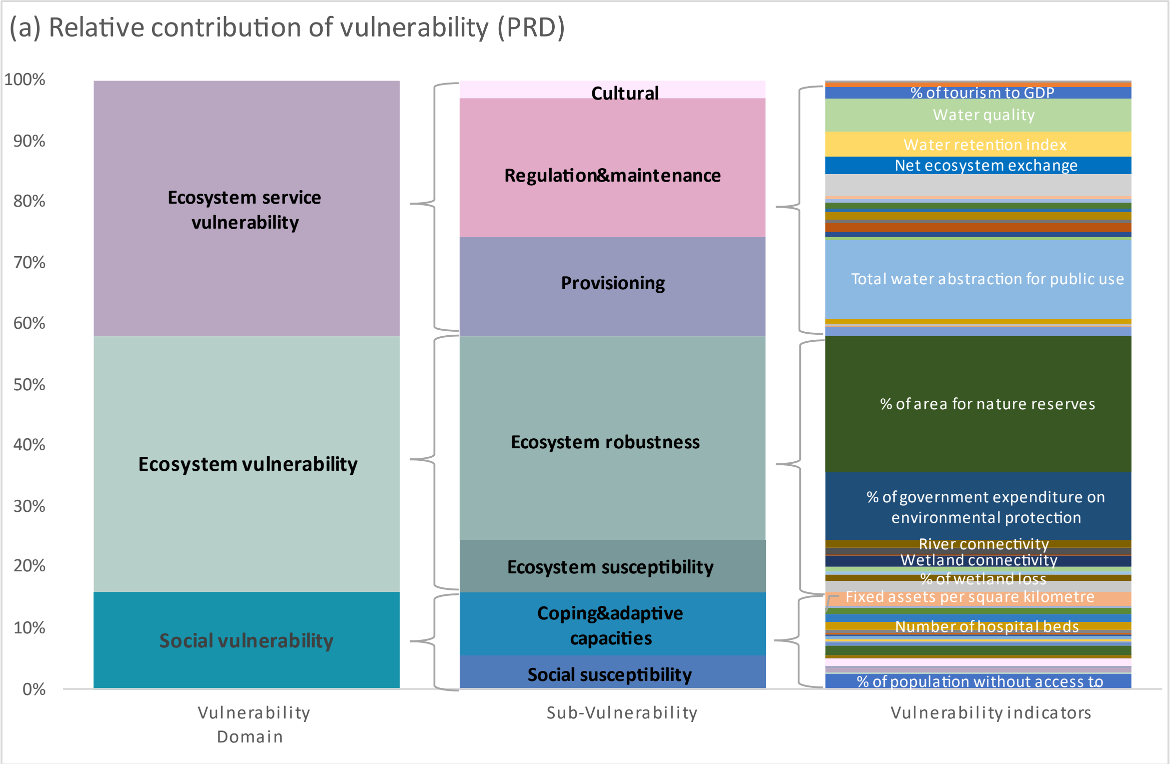
3.3.2 Risk component analysis

Overall, the PRD has higher multi-hazard exposure (mean value: 0.187) compared to the YRD (mean value: 0.127). The PRD is facing a high probability of hazardous events in the southern coastal regions, especially floods, cyclones and storm surges. The northeast coastal area of the YRD has the highest multi-hazard risk and is mainly affected by storm surges. There are also some areas in the western inland region that have higher multi-hazard risks because of the high exposure to drought, such as Anqing and Tongling.

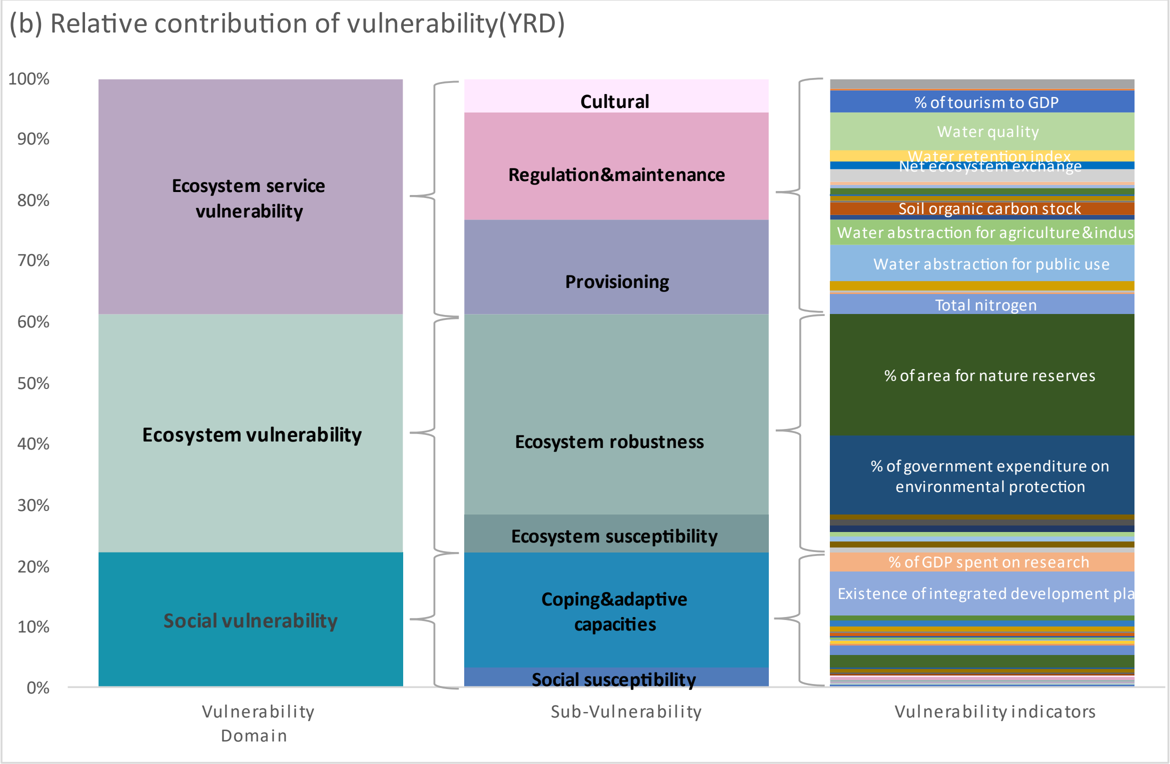
The analysis further indicates internal differences between the different risk components of the two deltas, especially the final distribution of vulnerability, even when the risk levels are similar. From the data in Fig. 3-7, we can see that while the overall vulnerability difference between the two deltas is not high (0.530 in PRD and 0.564 in YRD), the scores of different vulnerability components vary. The ecosystem and ecosystem service vulnerability in the PRD is slightly higher than the YRD, with the social vulnerability score lower than the YRD. This is mainly due to the difference in the scores of lack of coping and adaptive capacity between the two deltas, which are largely driven by social development and economic conditions.

Results for social vulnerability show discrepancies between developed cities and less economically developed areas both across and within the deltas. Areas with higher social vulnerability, especially the western and northern YRD, are predominantly characterized by areas of lower economic development. Further analysis reveals that the spatial distribution of social vulnerability is mainly driven by the scores of coping and adaptive capacity sub-components. Generally, both the western PRD and the northern YRD show higher ecosystem vulnerability. Breaking down the ecosystem vulnerability into ecosystem susceptibility and ecosystem robustness reveals high overlaps between ecosystem vulnerability and robustness. Ecosystem susceptibility mainly contributes to the low to moderate levels of ecosystem vulnerability in the central YRD. As for the ecosystem service component, Zhaoqing and Huizhou in the PRD, as well as the western and southern YRD, show higher vulnerability scores. These higher scores are shaped by different sub-components; for instance, decomposed scores of provisioning, regulation & maintenance, and cultural services contribute predominantly to vulnerability scores in the southern YRD, Huizhou of PRD, and the western YRD, respectively.

Combining the spatial distribution of SES vulnerability with the other three components indicates spatial variations in the overlapping areas of final vulnerability and other components. Following Hagenlocher et al. (2018), we drew the relative contribution of vulnerability in the two deltas (Fig. 3-8), which allows the identification of sub-vulnerability components and indicators that have relatively high contributions to the final vulnerability score. Key drivers of social vulnerability in both deltas include indicators of no access to clean water, public health expenditure and funding for scientific research and development. Deforested areas and low river connectivity in the PRD and wetland loss in the YRD are important drivers of ecosystem susceptibility. Besides, vegetation greenness (NDVI) has a high influence on ecosystem susceptibility in the two deltas. Low coverage of nature reserves and insufficient government expenditure on environmental protection, which belong to ecosystem robustness, are both critical factors for the final vulnerability scores. The relatively high contribution of these two indicators is also related to being assigned high weights of 11.8% and 10.7%. The vulnerability distribution in the two deltas is mainly driven by ecosystem services and ecosystem vulnerability, with social vulnerability, though assigned a weight of 33%, making a relatively low contribution (PRD: 16%, YRD: 22%).



(a) Relative contribution of vulnerability (PRD)



(b) Relative contribution of vulnerability(YRD)

Figure 3-8 (a) and (b): Relative contributions of the vulnerability domains, sub-vulnerability components and vulnerability indicators to the final vulnerability score in the PRD and YRD.

Regulation & maintenance services in the vulnerability of ecosystem services include important drivers, especially in soil quality, erosion control, climate, water and biodiversity. Water regulation (water retention index and water quality index) is the most critical factor affecting each delta's ecosystem services and final vulnerability. In terms of provisioning services, agriculture production (biomass) and water abstraction for public use (water sources) are the important drivers in the two deltas. Total water abstraction for agriculture and industry use (water sources provisioning) in YRD also contributes significantly to the final vulnerability score. Additionally, percentage of tourism to GDP is an important driver of cultural services in PRD and YRD. The ecological vulnerability (ecosystem service and ecosystem vulnerability) contributed 84% (ecosystem services accounted for 42%) in PRD and 78% (ecosystem services accounted for 39%) in YRD. This information can help develop targeted risk policies from the perspective of environmental strategies.

3.4 Discussion and outlook

3.4.1 Mapping risks to identify priority issues

Indicator-based risk assessment combined with GIS has proven to be an informative tool for assessing spatial risk distribution and helping management at all levels to take appropriate actions to reduce risks. There are two main categories of contributions from this research. One is to the existing risk assessment research, the proposed Delta-ES-SES framework with modular indicator list method has several advantages: (1) It allows collecting a large number of different data, and regularly updating the original data to obtain new risk scores. Risk scores can be easily analysed spatially, allowing managers to capture information at different scales; (2) This framework can adjust indicators and weights according to the specific situation or development goals of each region and can incorporate new hazard types and indicators; (3) Integrating the concept of ecosystem services into the vulnerability domain allows capturing the health status of ecosystems, but also facilitate identifying the corresponding contribution of ecosystem service to vulnerability and risk. Furthermore, incorporating customized ecosystem service-based protection measures into risk management and reduction ensures that ecosystems sustainably deliver services to human and social systems; (4) A detailed and subdivided multi-level indicator library allows scientists and experts to connect hazards with vulnerability and risk concepts, and be more capable of taking risk-informed decisions.

The other contribution is to the wider community, as our results clarified the risk levels of the two studied deltas. Risk assessments at the delta and city level primarily serve to identify areas with higher incidences of natural hazards, higher levels of economic/population/ecosystem exposure, vulnerability and risks in the study sites (such as Zhongshan in PRD and Taizhou_J in YRD), which constitutes the key prerequisites for developing effective risk reduction strategies. The final risk distribution aligns with findings in other studies concerning the risk of the YRD, where the southeastern region consistently exhibits high-risk distribution (Bai et al., 2023; Ou et al., 2022). As areas prone to natural hazards are likely to experience more recurring and intense extreme events in the future (Schwarz and Kuleshov, 2022), there is a need for more precise risk assessments at small spatial scales (urban-rural or village level). This process can better incorporate local knowledge and at the same time improve local understanding of risks at different levels. Collaboration, preparation and mitigation solutions across sectors and scales help advance risk assessments (Quesada-Román and Campos-Durán, 2023).

The analysis shows that the magnitude of risk in an area does not always match the underlying vulnerability, with situations of low vulnerability-high risk and high hazard exposure-low risk. This type of information can be used as supporting evidence for the potential effectiveness of existing decision-making with respect to risk reduction measures. For example, the high-risk but low-vulnerability tract of Yancheng in the YRD could suggest there might be certain useful risk prevention and control measures to reduce vulnerability that have been implemented in areas highly exposed to multiple hazards. High values in frequency, intensity, exposure and vulnerability have jointly led to high-risk levels, including in Zhongshan and Foshan in the PRD, and in the Yangzhou and Taizhou_J in YRD, which urgently need attention. Comparative studies have shown that even though study areas both belong to coastal river deltas, they face different major natural hazards. Breaking down multiple hazard components shows that the PRD faces a high intensity of cyclones and storm surges, while the YRD is more exposed to drought. These findings are in line with two separate assessments of typhoon risk in China, with the PRD identified as the significant risk hotspot, followed by Zhejiang Province in the YRD (Sajjad et al., 2020; Yin et al., 2013). While not reflected in the calculated risk index, we acknowledge the significance of other hazards in the delta regions, such as Harmful Algal Blooms (toxic red tide in the study area) mentioned during the expert consultation, with official reports confirming its occurrence in

Shenzhen of PRD and several areas of YRD (DNR, 2020).

The distribution of exposed population and economic values, denoting social exposure, typically exhibit consistent trends. The definition of ecosystems does not encompass artificial surfaces, potentially leading to disparities in spatial distribution between ecosystem exposure and social exposure. In densely developed areas, such as the majority of the PRD, social exposure levels are higher than ecosystem exposure. Through an examination of the spatial profiles in risk, hazard * exposure, and vulnerability, we noted a convergence of multi-hazard risk and hazard exposure scores, implying that the disparities in risk are noticeably associated with hazard magnitude and extent. The future trends in risks are significantly impacted by the variability and distribution of hazard events, highlighting the key to monitoring these, especially at the regional level (Tessler et al., 2015). Using advanced machine learning models to simulate, monitor and predict hazardous events has been proven effective in hazard description and risk assessments (Abu El-Magd et al., 2022; Antzoulatos et al., 2022; Mallick et al., 2021; Pourghasemi et al., 2021; Towfiqul Islam et al., 2021; Wang et al., 2015). These techniques deserve further exploration, such as exploring the impact of cascading hazards to enhance future risk mitigation and reduction measures (Komendantova et al., 2014).

3.4.2 Policy implications of vulnerability component

Priority 1 of the Sendai Framework for Disaster Risk Reduction 2015-2030 underscores the need to comprehensively grasp all dimensions of risk, encompassing vulnerability and the environment, to inform effective risk management (UNDRR, 2015). It is important to assess their social and ecological vulnerability to better minimize damage to social systems or ecosystems. The effects of vulnerability indicators in risk assessments are not equal in all cities, and they affect trends in each vulnerability sub-component differently. Multiple social sectors are exposed to natural hazards, especially the urban areas are highly vulnerable to multiple hazards due to population concentration and infrastructure density (Jones et al., 2015). For social susceptibility, the indicators 'percentage of population without access to clean water' and 'percentage malnourished population' of PRD and 'percentage of families below the poverty line in total households' of YRD are the main influencing factors. In addition to the common key driver of 'GDP per capita', the indicators 'number of hospital beds per 1,000 inhabitants' and 'public health expenditure' were found to be the driving factors affecting the coping capacity of the PRD. This means that the improvement of the medical system is an angle worthy of attention in future risk response in the PRD. Meanwhile, environmental protection policies and scientific research funding would have a relatively large impact on the adaptive capacity when facing risks. This study further highlights the key drivers such as forest and wetland loss for ecosystem health, consistent with risk assessment in the Mississippi Delta (Anderson et al., 2021).

Systematically incorporating ecosystem services into the vulnerability domain enables a more integrated understanding of the health of ecosystems and their ability to provide services that are directly or indirectly linked to vulnerability components. Ecosystem services capture the intricate interactions between humans and nature, and serve as a common link between social and ecosystem vulnerability. It is an opportunity to understand better the environmental dimension of risk profiles. Meanwhile, ecosystem services are also closely related to concepts such as ecosystem-based adaptation (EbA), nature-based solutions (NBS) and ecosystem-based disaster risk reduction (Eco-DRR) (IPCC, 2022a; Shah et al., 2023), which have been increasingly accepted to help people adapt to adverse effects of climate change (Seddon et al., 2020) and to reduce risks from natural hazards (Shah et al., 2020). As mentioned before, the key role of water sources (provisioning service) and water quality (regulation & maintenance) reflects the high dependence of delta development on ecosystem services, especially in the Anhui Province (inland of YRD). It connects risk management to water resource management and water policy related to the restoration of aquatic ecosystems (Grizzetti et al., 2016). Conducting vulnerability assessments from biophysical (water quality) and economic (water abstraction) highlights the interdependence of humans and ecosystems. Likewise, agricultural productivity is the key human activity in both deltas, not only directly related to human well-being but also reflecting the need for risk management in areas highly dependent on agriculture (or other biomass productivity). This could inspire a range of ecosystem-based sustainable conservation practices in agroforests and farmland, which also maintain and improve ecosystem services such as food provision, soil nutrient regulation and climate regulation (Blaser et al., 2018). Cultural context is also an aspect of vulnerability, and it includes valuable cultural components such as heritage and tourist attractions. The number of nature reserves and the development of tourism are important for understanding the stability of ecosystems. All of these introduce the method of assessing SES with the role of ecosystem services to sustainably manage, protect and prevent damage to ecosystems and their services (De Lange et al., 2010). Even in hazard-prone regions, better SES health can be achieved in long-term and sustainable ways by conserving natural resources and landscapes.

3.4.3 Limitations and way forward

To the best of our knowledge, our study is the first to conduct comparative SES-based risk assessments in the YRD and PRD regions and with a framework that incorporates the role of ecosystem services. Identifying areas with high-risk levels in these two most prosperous, densely populated, and hazard-prone areas is an effective way to reduce the negative impact of multiple natural hazards. Its application has certain limitations, such as the uncertainty brought by the use of expert weights (Gonzalez-Ollauri et al., 2023). In order to address this issue, we compared and analysed different risk profiles with expert weights and equal weights, and found that there were no obvious differences in risk scores. Nonetheless, the influence of expert-assigned weights on the relative contribution of vulnerability subcomponents and their respective indicators is an unavoidable factor. The accuracy of the data also needs to be continuously improved. It should be noted that the risk assessment relies on differences in various components across regions. In this study, we made maximum use of available spatial data as well as existing data appropriate to the study area. However, some data on vulnerability indicators were not available for small administrative regions, so we had to use average provincial data and profile the risk map at the city-level. We deem this has only a minimal impact on the final risk score, as provincial units can illustrate differences in development and management levels for the Yangtze and Pearl River Deltas. Although the city-level risk profiles may not always align directly with the scales of actions or policies, these results can effectively provide a foundation for targeted resource allocation, e.g., prioritizing areas for adaptation projects. Because of this, we cannot directly capture the distinction between urban and rural areas, yet key drivers of vulnerability may differ in rural and urban areas (Kc et al., 2021). Due to the distribution of diverse ecosystem types, significant differences may exist in the supply of ecosystem services between urban and rural areas. We, therefore, emphasize the necessity for future research to zoom in on the selected cities in the deltas to the county level to capture urban-rural differences for the development of more targeted regional policy and action plans.

Despite the emphasis on the progress of SES theory, the practices still bring inherent limitations, that is, it is difficult to identify specific coupling dynamics and other synergies (Anderson et al., 2021). We added the ecosystem services perspective and expert judgments to address this and better characterize the vulnerability and risk distribution. Various ecosystems offer different primary ecosystem services; for instance, mangroves contribute to biodiversity preservation and mitigating the adverse effects of coastal natural hazards, and their restoration is widely recognized as an ecosystem-based adaptation approach (Chausson et al., 2020). This also further emphasizes the data availability of ecosystem service indicators, especially for specific ecosystem types, which can be combined with high-resolution spatial data sets and local residents' perceptions of various services. Moreover, although static and spatially explicit approaches are highly realistic models, they fail to take into account interactions between adjacent areas, which is the inevitable compromise between complexity and practicality to represent reality in risk assessment (Anderson et al., 2021).

Quantifying stakeholder values of ecosystem services (requiring downscaled research) or system modelling (technically complex) in an SES vulnerability context at delta scales poses challenges. Therefore, we adopted an interdisciplinary approach to build on existing ecosystem service classifications and related research results, using this information to develop indicators which allowed us to compute indices. Our analysis of ecosystem services also reflects trade-offs in reducing complexity which brings its own limitations. What is needed in future research is small-scale studies with high-resolution spatial data and local stakeholders’ involvement to facilitate more reliable assessment and comparison of spatially distributed risks. The application of proxy indicators also causes uncertainty, which calls on management departments at all levels to pay attention to data collection and management (Hagenlocher et al., 2018), and can further improve and supplement the indicators selected for risk dimensions in subsequent research. Additionally, the uncertainty after the COVID-19 pandemic is not considered, which affects the development of social-ecological systems, especially socio-economic activities.

Beyond these practical applications in study sites, this framework also has several potential uses in theoretical and methodological improvements and extended applications for future research. On the one hand, this study captured the role of ecosystem services in risk assessments, which means the methodological advancements in quantifying ecosystem services can be integrated into risk assessments. Future research can build on this through the use of more advanced tools and interdisciplinary knowledge that validate and enhance vulnerability and risk assessment results. This can include incorporating more high-resolution spatial data (tools: machine learning, remote sensing, and GIS-based tools) and localized data (tools: participatory approaches), and combining them with the high-resolution data used in this study. On the other hand, current data and findings provide risk analyses of the two deltas over the past period, allowing longitudinal studies that track vulnerability and risk changes over time. This process can track the short-term and long-term effectiveness of disaster risk reduction strategies, and also help to identify environmental changes and new threats posed by hazards. Meanwhile, this study has developed a set of risk indicators that can be adjusted and applied to different contexts, facilitating the comparison of cross-region and global applications in vulnerability and risk patterns. Such analysis can help identify available practices and link these actions to broader global policy frameworks. This study will serve as the basis for further analysis of the deltaic multi-hazard risk index by incorporating ecosystem service indicators in the vulnerability domain. This aims to make the adjustable risk indicators and data in this study accessible to stakeholders in the study area and linked to ecosystem conservation measures or the deployment of nature-based solutions that can be implemented. In fact, this comprehensive framework and list of indicators can be replicated and adapted worldwide and is relatively easy to use. In the future, we can continue to explore the internal differences and develop a framework of ecosystem-based adaptation measures.

3.5 Conclusion

This paper applied an improved vulnerability and risk assessment framework for deltaic environments, mainly composed of applicable and easily accessible indicators. Vulnerability is quantified with indicators linking ecosystem services-based management measures and has been applied to the PRD and YRD. It also makes progress towards capturing the muti-hazard risk characteristics of all cities in the PRD and YRD regions exposed to five natural hazards (i.e. floods, typhoons, storm surges, droughts and salt intrusion). In addition to multi-hazard risk, a single-hazard risk profile is available for each region. Visualization maps allow users to readily compare and interpret the data distribution of each area for different risk attributes (hazard, exposure, and vulnerability). The risk index also allows looking at specific components and their indicators with high contribution to risk, some examples have already been given. Given the current divergence in spatial patterns of hazard exposure and social and ecological vulnerability within both deltas, future risk reduction planning should account for sub-component characteristics as well as individual/combined hazard impacts.

The importance of the proposed risk framework is that it directly and systematically incorporates ecosystem services and achieves the balance of social and ecological dimensions. It improved a lot on clarifying (multi-)hazard risk components and provided an integrated view for risk assessments of social-ecological systems. While previous work can also discern key risk indicators, the proposed methodology can explicitly extract ecosystem service indicators that affect human well-being, and which can be optimally used to inform current risk reduction and nature-based solutions practices.

Data availability

Data produced by this chapter are available in https://doi.org/10.1016/j.ocecoaman.2023.106980

4. Ecosystem-based adaptation strategies for multi-hazard risk reduction and policy implications in the Pearl River and Yangtze River deltas, China

Status: Submitted to International Journal of Disaster Risk Reduction. Under Revise & Resubmit.

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Abstract

There is growing interest in ecosystem-based adaptation (EbA) as an approach for climate change adaptation, disaster risk reduction, and the achievement of sustainable development goals. Its practice emphasizes the co-benefits of ecosystem protection and restoration, such as reduced exposure to various natural hazards, reduced social and ecological vulnerability, and enhanced livelihood resilience. The establishment of localized EbA initiatives to effectively respond to climate change requires an integrated assessment encompassing the understanding of dynamics of the local social-ecological system. Here, we use two risk assessment frameworks that comprehensively consider social and ecological dimensions of risk. The Global Delta Risk Index (GDRI) addresses social susceptibility, coping and adaptive capacity, ecosystem susceptibility and ecosystem robustness as core components of vulnerability. The DELTA-ES-SES framework, which is derived from the GDRI, additionally considers the intensity of multiple hazards and the importance of ecosystem services. Using both frameworks, we (1) show the distribution of high disaster risk areas in the Pearl River and Yangtze River deltas, (2) analyse the differences in regional vulnerability and risk levels caused by different risk components within the deltas, (3) identify key ecosystem services that relate to disaster risk, (4) outline EbA designs applicable to priority regions, and (5) provide policy suggestions for future plans. In doing so, we highlight the linkages between the role of ecosystem services, current EbA practices, and global/national policies to promote the success of EbA in regions exposed to natural hazards.

Keywords

Ecosystem services; Disaster risk reduction; Climate change adaptation; Risk assessment; Vulnerability; Environmental policies

4.1 Introduction

4.1.1 Climate change, disaster risks, and risk hotspots

Globally, climate change is exacerbating climate-related risks with increased frequency and intensity of some extreme events (Magnan et al., 2021). The loss and degradation of habitats also intensify the adverse impacts of climate change and extreme events on biodiversity and other ecosystem services (IPCC, 2022a). Between 2000-2019, climate-related disasters affected over 4 billion people and caused nearly US$2.97 trillion in global economic losses (CRED and UNDRR, 2020). These such events are also affected by social, economic and environmental changes that affect exposure, vulnerability and adaptive capacity of social-ecological systems (SES) (Hill et al., 2020; Oppenheimer et al., 2019; Tessler et al., 2016).

Some landscapes are more at risk than others. Covering less than 0.6% of the global land, yet home to 4.5% of the population and underpinning food production and urban expansion, deltas are seen as risk hotspots of global social and economic importance (Edmonds et al., 2020; Kuenzer et al., 2020; Tessler et al., 2015). Their dynamic network and low-lying characteristics make the deltaic environments susceptible to processes such as human activities, upstream changes, sea level rise and extreme climate-related events (Nicholls et al., 2020). Deltas are exposed to multiple natural hazards, exacerbated by anthropogenic and climate change impacts (IPCC, 2022a). For example, China is severely affected by disasters associated with natural hazards, particularly in the Pearl River and Yangtze River deltas, which are identified as high-risk areas for hydrometeorological events (Kundzewicz et al., 2019).

Risk assessments, critical in determining and reducing risks at various spatial scales, help to identify exposure and vulnerabilities to multiple hazards (Gallina et al., 2016). Emerging research suggests that indicator-based assessments are effective when performing risk analysis on large deltas (Hagenlocher et al., 2018; Scown et al., 2023; Tessler et al., 2015). In particular, SES-based multi-risk frameworks allow an understanding of environmental responses and sustainability issues from the risks associated with socioeconomic activities and ecological processes, including anthropogenic changes, supply of natural resources and ecosystem stability (Peng et al., 2023, also Chapter 2; Sebesvari et al., 2016).

4.1.2 Ecosystem-based adaptation to disaster risk reduction

Disaster risk reduction (DRR) measures need to be both cost-effective and able to cope with potential future climates (Nehren et al., 2023). Recent recognition of synergies and co-benefits in adaptation measures has prompted a transition from traditional hard infrastructure to ecosystem-based adaptation (EbA) (Jones et al., 2012; Shah et al., 2023). EbA is defined by the Convention on Biological Diversity (CBD) as “the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change” and is also seen as a specific type of nature-based solution (NbS) for climate change adaptation (CCA) (CBD, 2009; Cohen-Shacham et al., 2016). Such strategies mainly address climate-related hazards and climate change impacts, while ecosystem-based DRR (Eco-DRR) also includes non-climate-related hazards such as earthquakes (CBD, 2019). Recognizing that many EbA measures can be viewed as Eco-DRR measures linked to climate-related hazards, this study focuses on the role of EbA within the context of climate-related risk reduction in deltaic environments.

EbA considers ecosystems as key assets to help increase resilience to disasters and climate change and emphasises ecosystem integrity and the various ecosystem services they provide (Whelchel and Beck, 2016). Indeed, the benefits of EbA practices in various ecosystems such as forests, rivers, wetlands, and coastal areas, include reducing exposure and risks to natural hazards, improving natural protection, and increasing community livelihood resilience (Chapin et al., 2006; IPCC, 2022a; Luo et al., 2023; Renaud et al., 2016; Shah et al., 2023; Thomas et al., 2016). EbA can also provide extensive additional benefits at regional levels, such as green roofs and urban green open spaces that not only reduce risks from pluvial flooding, but also provide improved physical and mental health benefits (Cohen-Shacham et al., 2016; Hobbie and Grimm, 2020). EbA provides multiple benefits and sustainability characteristics, addressing both environmental and social vulnerabilities while enhancing the resilience of SES to climate change impacts (Doswald et al., 2014). These strengths align with global and regional policy frameworks, as outlined in section 4.1.3, which emphasize the role of ecosystems in climate change adaptation.

The EbA criteria formulated by FEBA (2017) emphasize the importance of EbA in reducing SES vulnerability and enhancing ecosystem health through restoration, maintenance, or improvement, while concurrently generating social benefits. Additionally, these criteria encompass multi-level policy support and the promotion of equitable local governance (FEBA, 2017). The development of EbA is based on the formulation of policies and strategic planning, interdisciplinary knowledge integration (covering economic, institutional, cultural, technological, environmental and other factors), and the collaborative engagement of practitioners from various sectors (Singh et al., 2020). Therefore, there are several challenges in the development of EbA measures, such as community-level determination of priority targets, how to turn targets into assessable evidence-based options, specific cost monitoring, and social acceptability (Ossola and Lin, 2021; Singh et al., 2020). In several cases, a lack of specific understanding of the local situation and appropriate application scales has impeded the manifestation of positive outcomes of various EbA options (Nalau et al., 2018). These challenges and limitations manifest as weaknesses in EbA implementation and gaps in current research, including knowledge gaps (limited empirical data and the need for more data to understand the performance of EbA actions under local environmental settings), funding and governance-related constraints, and uncertainties in implementation processes and results (requiring a long-term perspective to monitor effectiveness) (IPCC, 2022a).

There is a range of processes for planning and implementing EbA approaches, mainly including understanding and identifying SES vulnerability and risks, determining EbA and their priority options, project design, and monitoring expected outcomes (CBD, 2019). Thus, assessment frameworks are important to identify the frequency/intensity of and exposure areas from natural hazards under climate change, taking into account the multifunctional characteristics of EbA, i.e. their multiple social, economic and ecological contributions, and allowing the capture of associated cost/benefits. Vulnerability and risk assessments offer multiple advantages in formulating EbA, for example in (1) identifying the main issues and key areas to be addressed, which are also the first phase of EbA development; (2) undertaking multifaceted vulnerability assessment of SES, which covers various indicators of coping and adaptive capacity, ecosystem services and integrity of various natural ecosystems; (3) enabling the participation of various stakeholders (experts, sectors, and local communities) to obtain professional/local knowledge and reduce uncertainty in EbA development, and multi-level indicator-based approaches also facilitate targeted local decision-making.

4.1.3 Current policy framework to support ecosystem-based adaptation

Ecosystem conservation/restoration has attracted increasing attention due to their potential to address disaster risks and facilitate CCA, especially following the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) (Seddon et al., 2020) and the adoption of the Sendai Framework for Disaster Risk Reduction (SFDRR) in 2015. Consequently, global policies and agreements, such as the Kunming-Montreal Global

Biodiversity Framework (GBF), the 2030 Agenda for Sustainable Development (SDGs), and the New Urban Agenda, recognize the interconnections between ecosystems and sustainable development. Developing and implementing robust approaches that consider the role of ecosystems in DRR and CCA is critical and is also in line with these global policy agreements.

As a signatory to the Paris Agreement, China has been actively engaged in the global climate change adaptation governance process under the multilateral policy framework (MEE, 2022). China has advocated the establishment of the Belt and Road International Cooperation Framework for Disaster Risk Reduction and Emergency Management, offering a new platform to address the challenges posed by climate change and natural hazards. This emphasizes the alignment with the SFDRR and SDGs, as well as their joint efforts to effectively address systemic disaster risks (MEM, 2021). Domestically, the implementation of the National Comprehensive Disaster Prevention and Mitigation Plan (2011-2015) and the National Meteorological Disaster Defense Plan (2009-2020) has advanced mitigation and adaptation to climate change in key sectors (Fu et al., 2021). The Chinese Government has also developed ecosystem protection and biodiversity conservation policies based on national and regional knowledge (Fig. 4-3 in section 4.2.3). Overall, the above global initiatives or goals have been implemented and addressed in "China’s National Plan on Climate Change (2014–2020)" to strengthen domestic adaptation actions (NDRC, 2014). The newly released "National Climate Change Adaptation Strategy 2035" in 2022 further strengthens the development direction of future climate change adaptation, especially the regional climate change adaptation actions for South China (Pearl River delta) and East China (Yangtze River delta), which emphasizes the role of nature-based solutions (MEE, 2022).

4.1.4 Aims of the research

This study utilises risk assessment frameworks to highlight potential risk reduction measures and adaptation strategies. We investigate the applicability of two frameworks developed for deltaic environments, the GDRI and DELTA-ES-SES, to explore regional differences in the impact of different risk components on vulnerability and risk distribution. A combination of qualitative and quantitative approaches are employed to (1) determine the spatial distribution of vulnerability and disaster risk in the Pearl River Delta and Yangtze River Delta, and assess how different integrations of the multi-hazard risk components affect the overall risk profiles; (2) analyse the extent to which social and ecological vulnerability indicators affect final vulnerability and disaster risk, respectively; (3) identify key ecosystem services and ecosystem vulnerability indicators, (4) summarize available EbA options to support the overall sustainable development plan, and (5) provide suggestions for the development of future actions to achieve overall and regional policy targets for disaster risk reduction and climate change adaptation.

4.2 Methods

Our methods on the stepwise approach developed by (CBD, 2019) for the design and effective implementation of ecosystem-based options. The ecosystem-based adaptation framework follows three key processes, starting with a regional vulnerability and risk assessment, narrowing to site-specific vulnerability analysis, and ultimately identifying possible EbA options from ecosystem services analysis (Fig. 4-1).

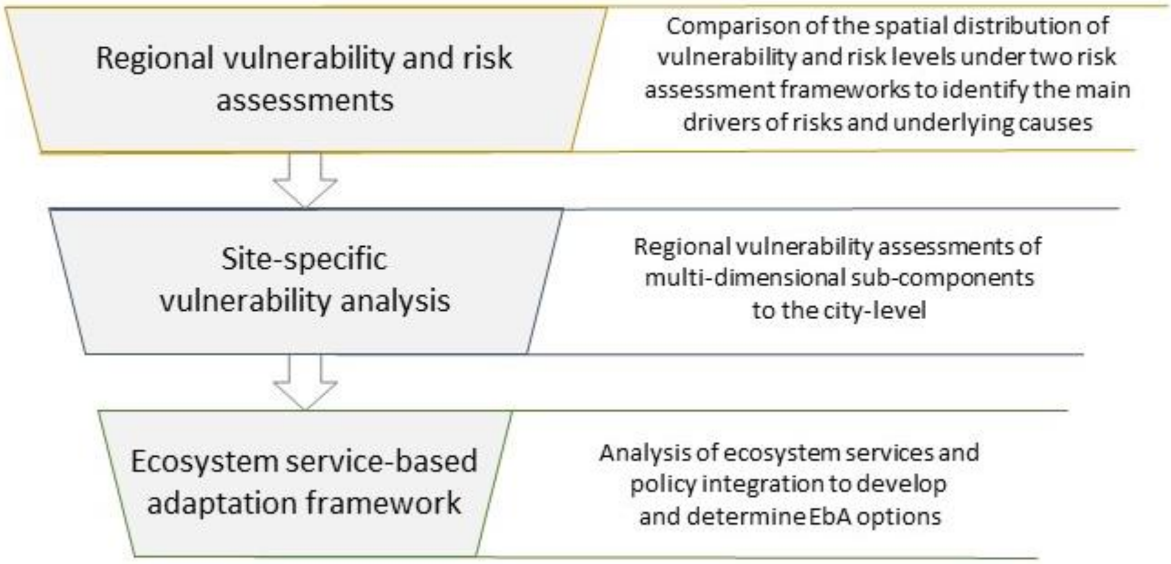
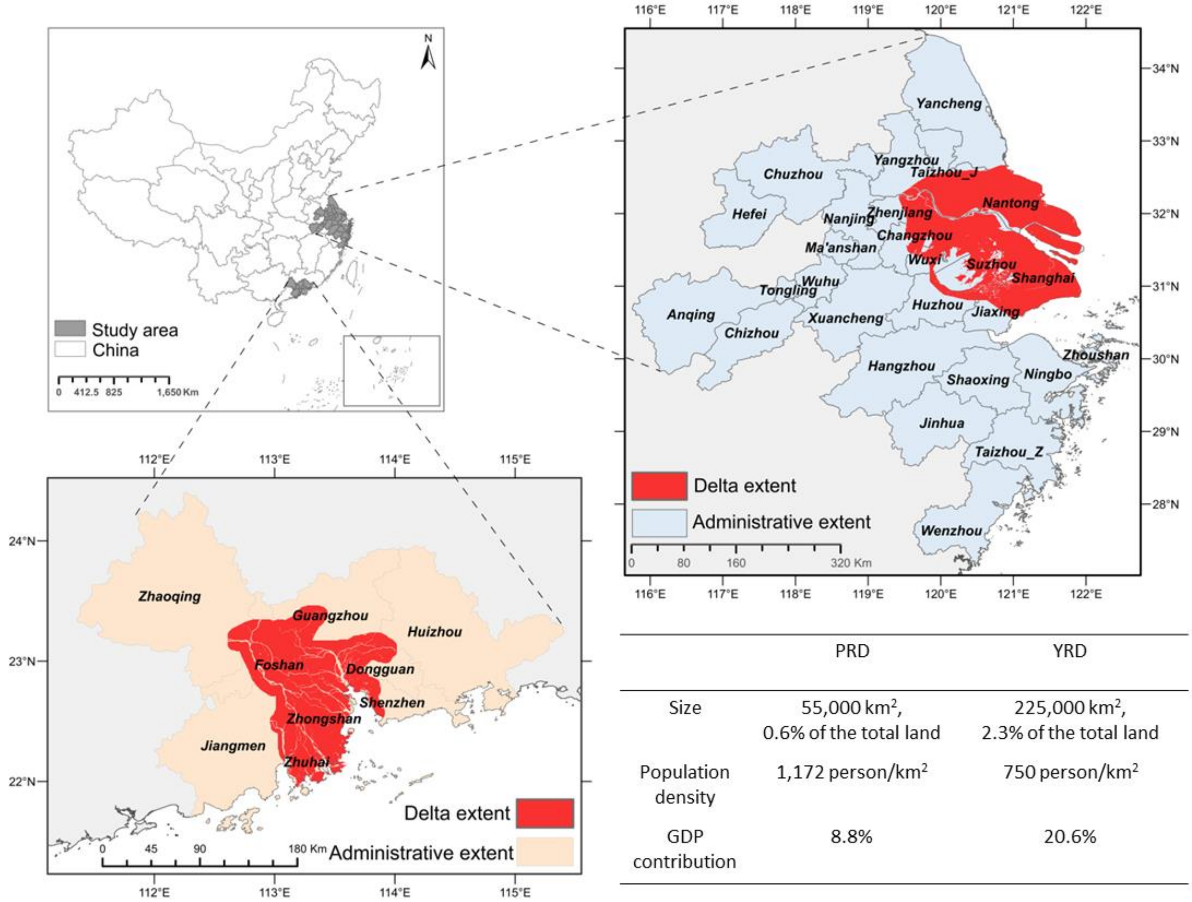


Figure 4-1 The 3-stepwise approach taken by an ecosystem-based adaptation framework, adapted from the stepwise approach developed by (CBD, 2019).

4.2.1 Study areas: Pearl River and Yangtze River deltas

The Pearl River Delta (PRD) is located in southern China's Guangdong Province (Fig. 4-2), which includes nine cities with an area of 55,000 km^2 and a population density of 1,172 persons/km^2, making it one of the most densely populated areas in the world (Nicholls et al., 2020). Here natural subsidence, high urbanization with infrastructure construction and rapid population growth have accelerated the fragmentation of the natural environment (Yang et al., 2015). These combined factors have also exacerbated the impacts of frequent natural hazards in the PRD, including tropical cyclones, flooding, storm surges, and droughts (Chan et al., 2021; Chen et al., 2016). The average annual direct losses caused by storm surges in the 2011-2020 period surpassed US$400 million (MNR, 2021). In most cities, like Guangzhou and Shenzhen, current urban drainage systems and adaptation planning are not enough to address the increasing hazard risks, particularly under future climate change trends (Chan et al., 2021).



	PRD	YRD
Size	55,000 km^2, 0.6% of the total land	225,000 km^2, 2.3% of the total land
Population density	1,172 person/km^2	750 person/km^2
GDP contribution	8.8%	20.6%

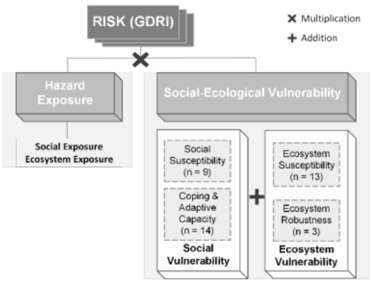
Figure 4-2 Map of Pearl River and Yangtze River deltas (bottom-left and top-right panels, respectively). The study areas are marked orange for Pearl River Delta and blue for Yangtze River Delta, based on GADM (2018). *Red areas show the deltas' geographic extent based on remote sensing images, from* Tessler et al. (2015). *Data for the table are from* NBS (2020).

Located on the eastern coast of China (Fig. 4-2), the Yangtze River Delta (YRD) is both densely populated and economically developed (Zhang et al., 2022). According to the Outline of the Yangtze River Delta Regional Integrated Development Plan, the YRD includes 27 cities across four provincial-level regions and spans 225,000 km^2 (The CPC Central Committee and General Office of the State Council, 2019). It is one of China's most important economic regions, constituting just 2.3% of the country's land area and about 10% of the population, but contributing more than 20% of the GDP (NBS, 2020). The people and economy of the YRD are increasingly threatened, as urban expansion, sediment reduction and subsidence, and sea level rise have caused increased coastal flooding, salinity intrusion, and degradation of mangroves (Kuenzer et al., 2020; Zhang et al., 2022).

Due to their key geographical and economic locations, the two deltas are regarded as significantly strategic regions to improve climate adaptability, especially in reducing the damage caused by meteorological and marine hazards, improving ecosystem services and implementing nature-based solutions (MEE, 2022). China currently still lacks comprehensive multi-dimensional or cross-regional assessments that can pinpoint critical areas for immediate attention (Fu et al., 2021). Hence, employing a quantitative indicator-based assessment approach holds practical significance in identifying crucial regions and sectors, and developing adaptation measures.

4.2.2 Risk assessment frameworks and their applications: the GDRI and the DELTA-ES-SES

The GDRI framework uses an aggregative modular structure for each risk component and focuses on deltaic SES as unit of analysis. It has been applied to various settings around the world (Anderson et al., 2021; Cremin et al., 2023; Feng et al., 2023; Hagenlocher et al., 2018; Shah et al., 2023). The DELTA-ES-SES framework is developed for coastal and deltaic SES to better understand the interactions between socioeconomic activities and biophysical processes by systematically incorporating the role of ecosystem services in risk analysis (Peng et al., 2023, also Chapter 2). The DELTA-ES-SES, is an adaptation of the GDRI that comprehensively considers environmental indicators, and aims to recognize key ecosystem services and in the process, inform EbA measures development (Peng et al., 2023, also Chapter 2). Hence, these frameworks are applicable to the PRD and YRD regions that are severely affected by multiple natural hazards but lack multi-hazard risk assessments, thereby contributing to disaster risk reduction. The characteristics, operation methodology and indicator selection of the two frameworks at our case study sites are presented in Table 4-1.

<table>
<tr>
<td>Framework structure</td>
<td>
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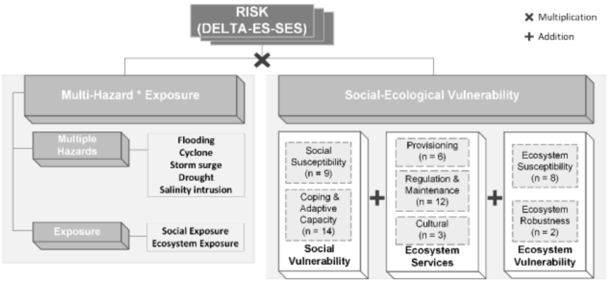
<td>
 </td>
</tr>
<tr>
<td>Shared characteristics</td>
<td colspan="2"><i>Hazards considered:</i> multiple hazards (Flooding; Cyclone; Storm surge; Drought; Salinity intrusion)
<i>Exposure considered:</i> social exposure (economics and population); ecosystem exposure
<i>Vulnerability considered: shared social vulnerability indicators; all ecosystem vulnerability indicators in the GDRI are included in the DELTA-ES-SES</i>
<i>Aggregation method</i><i>:</i> modular indicator library; equal weights applied
<i>Data pre-processing flow:</i> missing value analysis; outlier processing; multicollinearity check; rescaling (min-max normalization)
<i>Risk mapping:</i> spatial analysis; quantile classification</td>
</tr>
<tr>
<td rowspan="6">Differences</td>
<td colspan="2"><i>Risk composition</i><i>: the GDRI does not compute implicitly the hazard component</i></td>
</tr>
<tr>
<td>Risk = (Hazard) Exposure * Vulnerability</td>
<td>Risk = Hazard * Exposure * Vulnerability</td>
</tr>
<tr>
<td colspan="2"><i>Vulnerability domain</i>: the GDRI does not include an ecosystem service component implicitly</td>
</tr>
<tr>
<td>Vulnerability = Social Vulnerability + Ecosystem Vulnerability</td>
<td>Vulnerability = Social Vulnerability + Ecosystem Vulnerability + Ecosystem Services</td>
</tr>
<tr>
<td colspan="2"><i>Indicator distribution</i></td>
</tr>
<tr>
<td>Vulnerability indicators: social (59%); ecosystem (41%)</td>
<td>Vulnerability indicators: social (43%); ecosystem services (39%); ecosystem (18%)</td>
</tr>
</table>

Table 4-1 Framework comparison. The modular frameworks of GDRI and DELTA-ES-SES are adapted from Hagenlocher et al. (2018) *and* Peng et al. (2023)*, respectively.*

Comparing conceptual frameworks reveals shared characteristics of risk components, where hazard, exposure and vulnerability sub-components are aligned with the IPCC (2022a) definitions. When designing the frameworks, multiple environmental hazards (flooding, cyclones, storm surges, drought, salinity intrusion and pollution) are considered. Their applications are based on the conceptual framing of risk components, combined with indicator-based assessment methods that have been widely used for risk analysis (Anelli et al., 2022; Chen and Alexander, 2022; Hagenlocher et al., 2018; Nguyen et al., 2019).

The underlying indicator library was developed through previous identification of the deltas' social and environmental characteristics that contribute to risk assessments against multiple natural hazards (Hagenlocher et al., 2018; Peng et al., 2023; Sebesvari et al., 2016). An expert consultation was carried out to understand the socio-economic and environmental settings and determine final indicator lists for framework applications in the given two deltas. Additionally, both frameworks support the application of qualitative methods (experts/stakeholders involvement) to assign weights for each component and indicator, however, to reduce risk differences due to weight assignment, this study applied equal weights for risk components. Given the varying number of indicators within each component, the corresponding weight for each indicator varies according to the sub-component it belongs to. Data processing steps are set out in Appendix 8. Finally, risk mappings are based on the quantile classification which allows the interpretation of relative risk levels obtained by two risk indices.

Differing from the GDRI, the DELTA-ES-SES not only directly considered the potential occurrence of each hazard, but also analysed the ecosystem services as a component of the vulnerability domain. Differences are reflected in risk components (hazard, exposure and vulnerability), especially in the vulnerability domain and its indicators distribution. While (Hazard) Exposure in the GDRI only represented the exposed population, economics and ecosystems when facing multiple natural hazards, Hazard * Exposure in the DELTA-ES-SES refers to the multiplication of hazard and exposure scores, which combined the magnitude and affected extent of potentially hazardous events (Peng et al., 2023, also Chapter 2). When determining vulnerability, the GDRI defined the deltas from the perspective of social and ecological sub-systems with four vulnerability components: social susceptibility, lack of coping and adaptive capacity, ecosystem susceptibility, and lack of ecosystem robustness (Hagenlocher et al., 2018). There was a predominance of the socio-economic dimension (Hagenlocher et al., 2018; Sebesvari et al., 2016), with social vulnerability indicators representing 59% of all indicators, but was an improvement from other frameworks which had little consideration for the environmental dimension of risk (Sebesvari et al., 2016). The DELTA-ES-SES drew on the characterization of ecological and social processes across spatial and/or temporal scales in the notion of ecosystem services, incorporating them into the vulnerability domain (Peng et al., 2023, also Chapter 2). This approach aims to understand and respond to the interconnections between biophysical and social systems in the context of risk perceptions. After expert consultation and data collection, ecosystem services and social and ecosystem vulnerability were combined into vulnerability analysis, among which ecosystem services indicators accounted for 39% of total indicators.

Of the 54 vulnerability indicators in DELTA-ES-SES, 15 indicators (28%) are unique and belong to ecosystem services (provisioning, regulation & maintenance and cultural services). Appendix 9 provides data sources for the indicators applied to the GDRI and DELTA-ES-SES.

Although the GDRI and DELTA-ES-SES differ in their formulation of risk, they both aim to provide information on the spatial distribution of vulnerability and risks in SES exposed to natural hazards, and to allow for the development of targeted risk reduction strategies. The present comparative analysis aims to explain the influence of risk framework and indicator selections on the final risk scores. Analysing potential differences in risk distributions aims to provide decision-makers with supporting evidence for future environmental management from a perspective on ecosystem services.

4.2.3 The role of ecosystem services in the ecosystem-based adaptation framework

We combine ecosystem services analysis from previous vulnerability assessments with current global and national-scale policy formulations, to develop EbA measures that are consistent with development goals in the study region, as shown in Fig. 4-3. The analysis of the risk assessment outputs indicates the contribution of each indicator to the final vulnerability and risk scores. This approach helps to determine their relative importance, as well as to propose associated policies and solutions to reduce overall risks, including ecosystem-based measures. According to the vulnerability assessment results, the main ecosystem service types and their relative importance to final vulnerability can be determined for 36 cities of the two deltas.

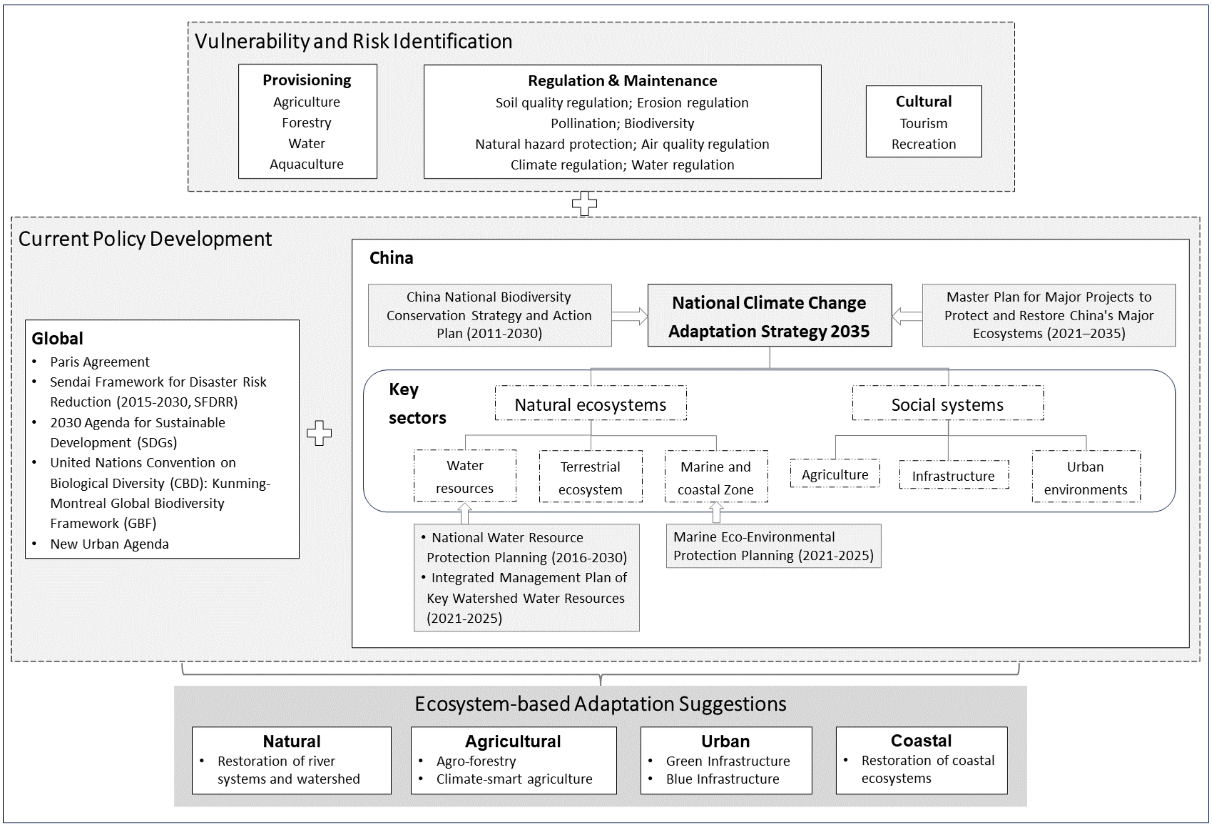


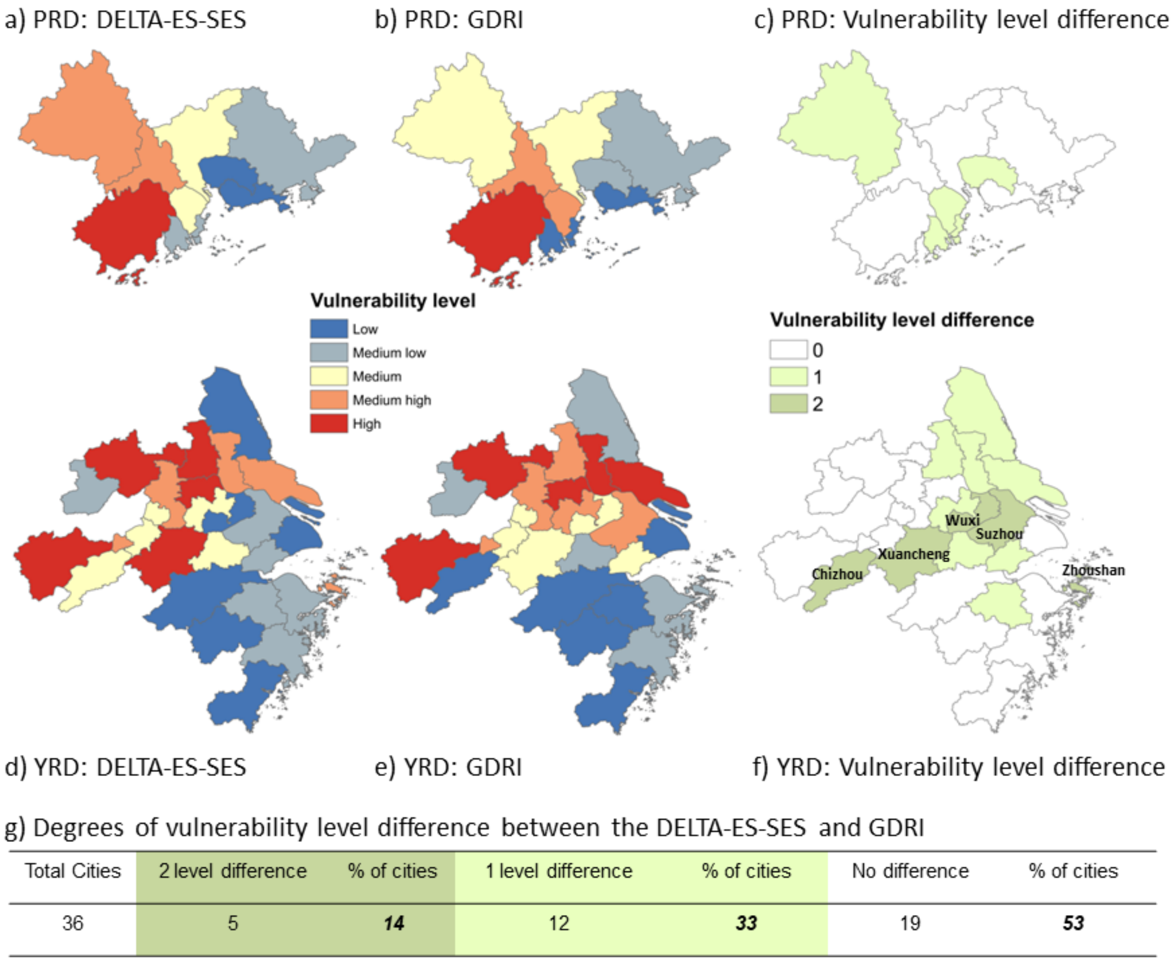
Figure 4-3 Approach used to develop an ecosystem-based adaptation strategies framework related to ecosystem services.

To develop an integrated plan that considers ecosystem conservation or restoration, sustainable development and climate change, we reviewed relevant policies and strategies at the national and global scales. This process allowed for the formulation of global, national, and regional strategies applicable to the social-ecological settings of the PRD and YRD regions and connected to the available EbA strategies. Finally, a number of EbA/NbS approaches related to ecosystem services worldwide were reviewed as feasible proposals based on regional risk configurations and current policy goals for the two deltas.

4.3 Results

4.3.1 Comparison of vulnerability assessments

We present the spatial distribution of the vulnerability scores derived from the application of the DELTA-ES-SES and GDRI frameworks (Fig. 4-4). Five cities in the northwestern region of the PRD and most of the north-central YRD showed medium to high SES vulnerability for the DELTA-ES-SES and GDRI frameworks, respectively. Following the methodology by Anderson et al. (2019), we show the degree of vulnerability level difference for each city, with 53% of the regions having the same vulnerability levels and no city showing 3 level differences (Fig. 4-4g). Differences were apparent in four cities of PRD (Fig. 4-4c) and the central and northeast regions of the YRD (Fig. 4-4f). Among the cities with two levels of difference, Chizhou, Xuancheng and Zhoushan in the YRD showed higher vulnerability with the DELTA-ES-SES.


a) PRD: DELTA-ES-SES
b) PRD: GDRI
c) PRD: Vulnerability level difference
d) YRD: DELTA-ES-SES
e) YRD: GDRI
f) YRD: Vulnerability level difference

g) Degrees of vulnerability level difference between the DELTA-ES-SES and GDRI

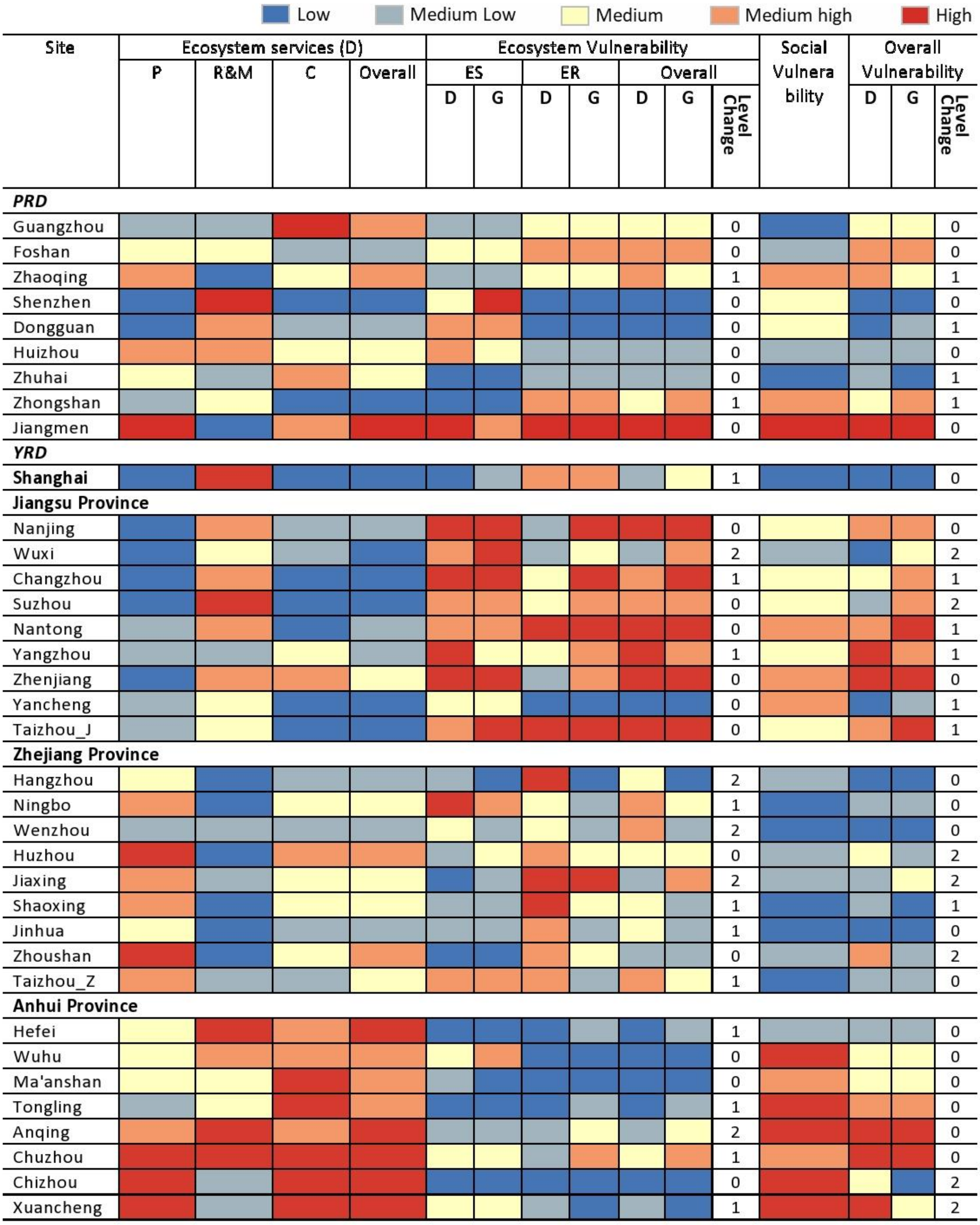
Total Cities	2 level difference	% of cities	1 level difference	% of cities	No difference	% of cities
36	5	***14***	12	***33***	19	***53***

Figure 4-4 SES Vulnerability assessed by DELTA-ES-SES: a) Pearl River Delta (PRD) and d) Yangtze River Delta (YRD); SES Vulnerability assessed by GDRI: b) PRD and e) YRD. Vulnerability score classifications are based on the quantile method; c), f) and g) Degree of vulnerability level difference between the DELTA-ES-SES and GDRI. 2 and 1 level differences indicate variations in vulnerability levels, encompassing both higher-to-lower and lower-to-higher scenarios.

Although social vulnerability accounts for a large portion of the indicators, the differences are mainly reflected in ecosystem services and ecosystem vulnerability. Social vulnerability calculated using the GDRI contributed 41% and 45% to the SES vulnerability in the PRD and YRD, respectively, while the social vulnerability calculated using the DELTA-ES-SES contributed 29% and 32% in the PRD and YRD, respectively. That is, the final vulnerability of both frameworks is more driven by vulnerability of ecosystem and ecosystem services. There are also 16 unique ecosystem service indicators in DELTA-ES-SES, which also cause differences in vulnerability distribution from the GDRI. In addition, the assignment of equal weights in the aggregation methodology for each vulnerability sub-component also led to differences, with social vulnerability assigned 50% in GDRI and only around 33% in DELTA-ES-SES.

4.3.2 Site-specific vulnerability analysis

We summarize comparative assessment results from vulnerability and its sub-components for each study site. The individual distribution to the vulnerability domain is divided into five levels from low to high through quantile classification (Fig. 4-5). Generally, relatively economically less-developed regions (e.g. Anhui Province) tend to exhibit higher social vulnerability, primarily due to lower levels of critical services, economic demographic development (e.g. higher proportion of illiterate population), as well as lower levels of coping and adaptive capacity. Conversely, economically developed regions often demonstrate lower vulnerability in these three dimensions. The sub-components comprising the indicators of social vulnerability of the two frameworks remain consistent, resulting in the same vulnerability level distribution.



🟦 Low ⬜ Medium Low 🟨 Medium 🟧 Medium high 🟥 High

Site	Ecosystem services (D)				Ecosystem Vulnerability							Social Vulnerability	Overall Vulnerability		
	P	R&M	C	Overall	ES		ER		Overall						
					D	G	D	G	D	G	Level Change		D	G	Level Change
PRD															
Guangzhou	⬜	⬜	🟥	🟧	⬜	⬜	🟨	🟨	🟨	🟨	0	🟦	🟨	🟨	0
Foshan	🟨	🟨	⬜	⬜	🟨	🟨	🟧	🟧	🟧	🟧	0	⬜	🟧	🟧	0
Zhaoqing	🟧	🟦	🟨	🟧	⬜	⬜	🟨	🟨	🟧	🟨	1	🟧	🟧	🟨	1
Shenzhen	🟦	🟥	🟦	🟦	🟨	🟥	🟦	🟦	🟦	🟦	0	🟨	🟦	🟦	0
Dongguan	🟦	🟧	⬜	⬜	🟧	🟧	🟦	🟦	🟦	🟦	0	🟨	🟦	⬜	1
Huizhou	🟧	🟧	🟨	🟨	🟧	🟨	⬜	⬜	⬜	⬜	0	⬜	⬜	⬜	0
Zhuhai	🟨	⬜	🟧	🟨	🟦	🟦	⬜	⬜	⬜	⬜	0	🟦	⬜	🟦	1
Zhongshan	⬜	🟨	🟦	🟦	🟦	🟦	🟧	🟧	🟨	🟧	1	🟧	🟨	🟧	1
Jiangmen	🟥	🟦	🟧	🟥	🟥	🟧	🟥	🟥	🟥	🟥	0	🟥	🟥	🟥	0
YRD															
Shanghai	🟦	🟥	🟦	🟦	🟦	⬜	🟧	🟧	⬜	🟨	1	🟦	🟦	🟦	0
Jiangsu Province															
Nanjing	🟦	🟧	⬜	⬜	🟥	🟥	⬜	🟥	🟥	🟥	0	🟨	🟧	🟧	0
Wuxi	🟦	🟨	⬜	🟦	🟧	🟥	⬜	🟨	⬜	🟧	2	⬜	🟦	🟨	2
Changzhou	🟦	🟧	🟦	🟦	🟥	🟥	🟨	🟥	🟧	🟥	1	🟨	🟨	🟧	1
Suzhou	🟦	🟥	🟦	🟦	🟧	🟧	🟨	🟧	🟧	🟧	0	🟨	⬜	🟧	2
Nantong	⬜	🟧	🟦	⬜	🟧	🟧	🟥	🟥	🟥	🟥	0	🟧	🟧	🟥	1
Yangzhou	⬜	⬜	🟨	⬜	🟥	🟨	🟨	🟧	🟥	🟧	1	🟨	🟥	🟧	1
Zhenjiang	🟦	🟧	🟧	🟨	🟥	🟥	⬜	🟧	🟥	🟥	0	🟧	🟥	🟥	0
Yancheng	⬜	🟨	🟦	🟦	🟨	🟨	🟦	🟦	🟦	🟦	0	🟧	🟦	⬜	1
Taizhou_J	⬜	🟨	🟦	🟦	🟧	🟥	🟥	🟥	🟥	🟥	0	🟨	🟧	🟥	1
Zhejiang Province															
Hangzhou	🟨	🟦	⬜	⬜	⬜	🟦	🟥	🟦	🟨	🟦	2	⬜	🟦	🟦	0
Ningbo	🟧	🟦	🟨	🟨	🟥	🟧	🟨	⬜	🟧	🟨	1	🟦	⬜	⬜	0
Wenzhou	⬜	⬜	⬜	⬜	🟨	⬜	🟨	⬜	🟧	⬜	2	🟦	🟦	🟦	0
Huzhou	🟥	🟦	🟧	🟧	⬜	🟨	🟧	🟨	🟨	🟨	0	⬜	🟨	⬜	2
Jiaxing	🟧	⬜	🟨	🟨	🟦	⬜	🟥	🟥	⬜	🟧	2	⬜	⬜	🟨	2
Shaoxing	🟧	🟦	🟨	🟨	⬜	⬜	🟥	🟨	🟨	⬜	1	🟦	⬜	🟦	1
Jinhua	🟨	🟦	⬜	⬜	⬜	⬜	🟧	⬜	🟨	⬜	1	🟦	🟦	🟦	0
Zhoushan	🟥	🟦	🟨	🟧	🟦	🟦	🟧	🟨	⬜	⬜	0	⬜	🟧	⬜	2
Taizhou_Z	🟧	⬜	⬜	🟨	🟧	🟧	🟧	⬜	🟧	🟨	1	🟦	⬜	⬜	0
Anhui Province															
Hefei	🟨	🟥	🟧	🟥	🟦	🟦	🟦	⬜	🟦	⬜	1	⬜	⬜	⬜	0
Wuhu	🟨	🟧	🟧	🟧	🟨	🟧	🟦	🟦	🟦	🟦	0	🟥	🟨	🟨	0
Ma'anshan	🟨	🟨	🟥	🟧	⬜	🟦	🟦	🟦	🟦	🟦	0	🟧	🟨	🟨	0
Tongling	⬜	🟨	🟥	🟧	🟦	🟦	🟦	⬜	🟦	⬜	1	🟥	🟧	🟧	0
Anqing	🟧	🟥	🟧	🟥	⬜	⬜	⬜	🟨	⬜	🟨	2	🟥	🟥	🟥	0
Chuzhou	🟥	🟥	🟥	🟥	🟨	🟨	⬜	🟧	🟨	🟧	1	🟧	🟥	🟥	0
Chizhou	🟥	⬜	🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟦	0	🟥	🟨	🟦	2
Xuancheng	🟥	⬜	🟥	🟥	🟨	🟨	⬜	🟦	⬜	🟦	1	🟥	🟥	🟨	2

Figure 4-5 Comparison of vulnerability and separate subcomponent levels between Delta-ES-SES (D) and GDRI (G) for each study site. P: provisioning service; R&M: regulation & maintenance service; C: cultural service; ES: Ecosystem susceptibility; ER: Ecosystem Robustness.

While ecosystem vulnerability and overall vulnerability between the two frameworks showed little difference, the scores for each sub-component of vulnerability demonstrate that the internal drivers vary, especially within the YRD. For instance, while both Zhenjiang in Jiangsu Province and Chuzhou in Anhui Province show high vulnerability, the former is mainly due to high ecosystem vulnerability, whereas Chuzhou's vulnerability is predominantly attributed to high levels of ecosystem service components. In addition to the ecosystem vulnerability of both frameworks, the inclusion of ecosystem services in DELTA-ES-SES can explain more of the multidimensional characteristics of vulnerability.

In order to test the influence of ecosystem service indicators on the vulnerability of the provinces, we determined the relative contribution of vulnerability sub-components to the final vulnerability score in the DELTA-ES-SES for PRD and four provincial units of the YRD to understand the differences and their internal drivers (Fig. 4-6). Overall, ecosystem services had the greatest impact on vulnerability scores in Anhui Province (35%), followed by Zhejiang Province (33%), PRD (28%), Jiangsu Province (27%), and Shanghai (25%). Data on the relative contribution of vulnerability subcomponents similarly show discrepancies between social-economic development. Shanghai and Jiangsu in the YRD, and the PRD are more economically developed regions, where the contribution of the primary industry is small, and the relative contribution of ecosystem service indicators to final vulnerability is also lower than in other regions.

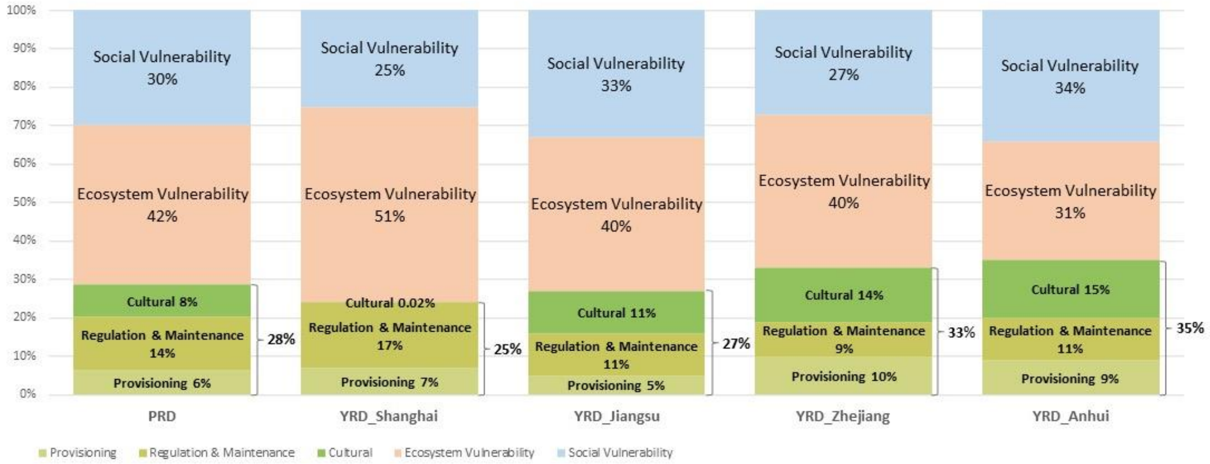
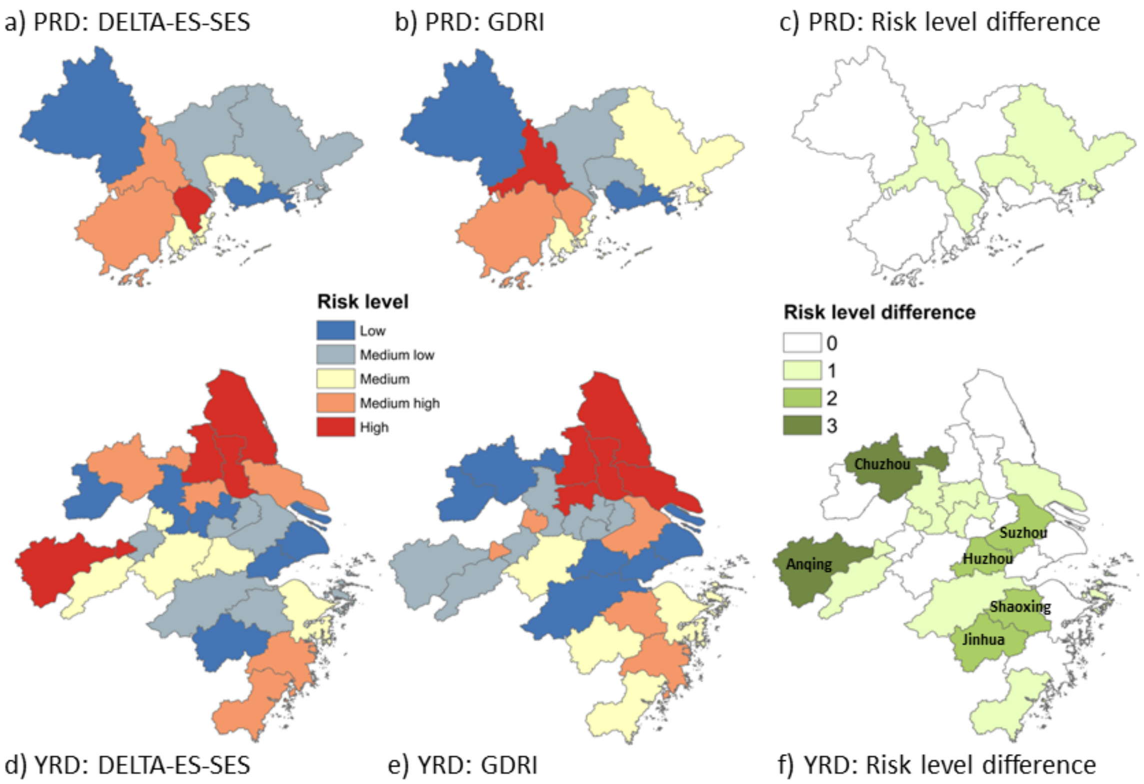


Figure 4-6 Relative importance distribution of three vulnerability components and ecosystem services sub-component of the DELTA-ES-SES framework for the Pearl River Delta (PRD), Shanghai, Jiangsu, Zhejiang, and Anhui Provinces in the Yangtze River Delta (YRD).

4.3.3 Comparison of risk levels

Differences in risk indices between the two frameworks can be easily identified, with three areas showing the same medium to high-risk distribution: the southwest of the PRD, the northeast and the southeast of the YRD. Low to medium-low risk levels predominantly cluster within the delta centre and inland regions, particularly in the central part of the YRD (Fig. 4-7).



g) Degrees of risk level difference between the DELTA-ES-SES and GDRI

Total Cities	3 level difference	% of cities	2 level difference	% of cities	1 level difference	% of cities	No difference	% of cities
36	2	***6***	4	***11***	14	***39***	16	***44***

Figure 4-7 Multi-hazard risk assessed with the DELTA-ES-SES: a) Pearl River Delta (PRD) and d) Yangtze River Delta (YRD); Multi-hazard risk assessed with the GDRI: b) PRD and e) YRD. Risk score classifications are based on the quantile method and are divided into Low, Medium low, Medium, Medium high, and High risk levels. c), f) and g) Degree of risk level difference between the DELTA-ES-SES and GDRI. 3, 2 and 1 level differences indicate variations in risk levels, encompassing both higher-to-lower and lower-to-higher scenarios.

Contrasting risk distributions indicates more differences compared to vulnerability domain within two deltas, with 44% of cities having the same risk level (Fig. 4-7g). Overall, six cities (17%) showed risk differences of two or three levels, implying relatively large shifts in overall risk results. The western region of the YRD in the DELTA-ES-SES shows high risks with completely different low-risk levels in the GDRI. The three-level differences of Anqing and Chuzhou are driven by the higher hazard * exposure levels in the DELTA-ES-SES than the (Hazard) Exposure levels in the GDRI, especially because of the severity of flooding in Anqing and drought in Chuzhou. Combined with the vulnerability level changes described above, this suggests that the final risk in the study areas is mainly driven by hazard severity.

4.3.4 Ecosystem service-based adaptation framework

Understanding the statistical relationship between ecosystem service indicators and risk levels helps to identify key drivers and develop targeted policy recommendations. Fig. 4-8a and 4-8b depict delta- and province-distributed differences in the importance of key ecosystem services that affect the overall risk profiles. When proposing strategies based on ecosystem services, it is possible to identify the areas where corresponding ecosystem services contribute more to vulnerability and prioritize interventions. The analysis of SES vulnerability for both frameworks allows the identification of the indicator contribution to the final vulnerability. Identifying key ecosystem services from the DELTA-ES-SES framework could provide more evidence-based information on risk reduction measures starting from ecosystem services indicators, which is also consistent with the development process of EbA.

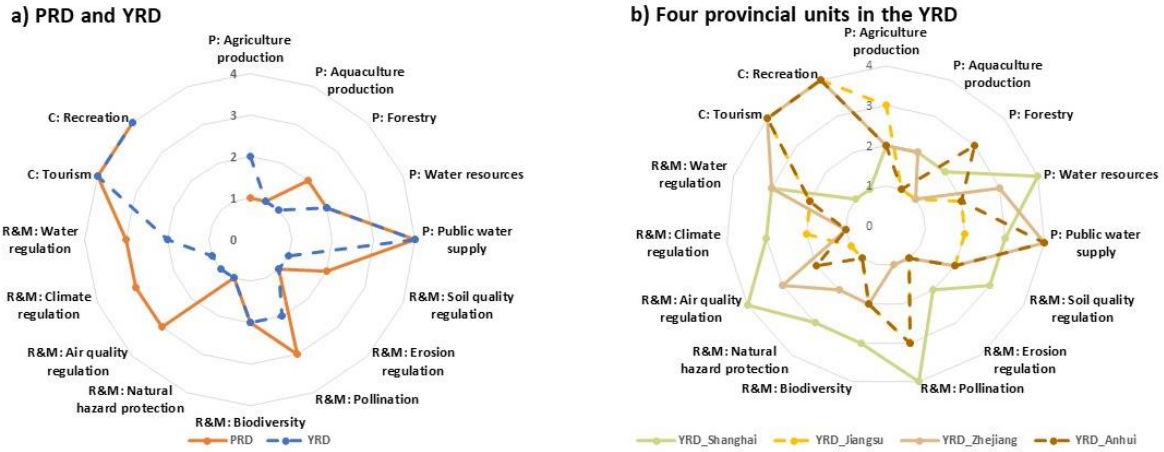


Figure 4-8 a) Relative importance distribution of main ecosystem services for the Pearl River Delta (PRD) and the Yangtze River Delta (YRD). b) Relative importance distribution of main ecosystem services for Shanghai, Jiangsu, Zhejiang, and Anhui in the YRD. Rankings are based on the relative distribution of each ecosystem service category to the final vulnerability score (quantile classification) on a scale of 1 to 4: minimum - 25th percentile, 25th - 50th percentile, 50th-75th percentile, and 75th percentile – maximum. P: provisioning service; R&M: regulation & maintenance service; C: cultural service. This methodology was also applied to obtain the importance distribution of ecosystem services for each city.

Using the above information, we may propose EbA strategies based on the main drivers of local-level disaster risks and previous EbA experiences. The DELTA-ES-SES framework supports the identification of ecosystem services in the context of an overall adaptation strategy to develop EbA measures to restore and improve ecosystem health. Meanwhile, ecosystem vulnerability indicators also provide information for further identifying entry points for EbA. Combining ecosystem service identification, EbA applications, and multi-dimensional policy targets, Table 4-2 lists possible measures, priority/effective zones and policy integrations based on ecosystem services with medium to high importance.

Table 4-2 Examples of key sectors with related ecosystem services with possible ecosystem-based adaptation strategies for the Pearl River Delta (PRD) and Yangtze River Delta (YRD). According to city-level data of ecosystem service importance distribution, regions with an importance of 4 are considered as priority/effective zones. References are for EbA strategies column. Only the key points of the policy are listed, please refer to the original document for details.

Key sector	**Agriculture** Related services: Agriculture production; Soil quality regulation	
EbA strategies	**Possible benefits from strategies**	**References**
Agricultural diversification; Agro-forestry; Climate-smart agriculture; Agroecology	Food security; income benefits; risk reduction (erosion, flooding, etc)	(Blaser et al., 2018; Steenwerth et al., 2014; Tamburini et al., 2020)
Connect to current policy	SDG 1 (no poverty) & 2 (zero hunger); Global Biodiversity Framework: Target 10 (emphasis on sustainable management of agriculture and forestry) National Climate Change Adaptation Strategy 2035: enhance the climate resilience of agricultural ecosystems; establish a climate-adaptable food security system; China National Biodiversity Conservation Strategy and Action Plan (2011-2030): sustainably utilizing bio-resources in the fields of agriculture, forestry, fishery and animal husbandry.	
Priority/ effective zones	PRD: Zhaoqing, Huizhou, Dongguan, Shenzhen; YRD: Jiangsu Province (except for Nanjing, Wuxi), Zhejiang Province (Wenzhou, Jinhua, Zhoushan, Taizhou), Anhui Province (Chuzhou, Xuancheng)	
Key sector	**Forestry** Related services: Forestry production	
EbA strategies	**Possible benefits from strategies**	**References**
Sustainable forest management: Site-adapted mixed species; Multi-functional forests; forest restoration	Water security; income benefits; risk reduction (flooding, cyclones, etc)	(Huang et al., 2012; Yousefpour et al., 2020)
Connect to current policy	SDG 6 (clean water and sanitation), 13 (climate action), & 15 (life on land); Global Biodiversity Framework: Target 10 (emphasis on sustainable management of forestry) National Climate Change Adaptation Strategy 2035: strengthen the protection of typical ecosystems and the restoration of degraded ecosystems; Master Plan for Major Projects to Protect and Restore China's Major Ecosystems (2021–2035): protection of natural forest resources; Yangtze River Key Ecological Zone	
Priority/ effective zones	PRD: Zhaoqing, Jiangmen; YRD: Anhui Province (except for Tongling)	
Key sector	**Water resources** Related services: Water resources; Public water supply; Water regulation	

<table>
<tr><th colspan="2">EbA strategies</th><th>Possible benefits from strategies</th><th>References</th></tr>
<tr><td colspan="2">Restoration of river systems and riparian vegetation and other natural flood risk management practices</td><td>Water security (quality and supply); biodiversity enhancement; risk reduction (floods)</td><td>(Chausson et al., 2020; Myers et al., 2019; Vermaat et al., 2016)</td></tr>
<tr><td>Connect to current policy</td><td colspan="3">SDG 6 (clean water and sanitation) & 13 (climate action);
Global Biodiversity Framework: Target 2 (emphasis on restoration of degraded ecosystems)

National Climate Change Adaptation Strategy 2035: enhance the ability to protect and manage the ecology of major rivers and lakes;
Master Plan for Major Projects to Protect and Restore China’s Major Ecosystems (2021–2035): water resources security;
Integrated Management Plan of Key Watershed Water Resources (2021-2025): water pollution prevention and control (primary goal: improving the water environment of the basin); National Water Resource Protection Planning (2016-2030).</td></tr>
<tr><td>Priority/ effective zones</td><td colspan="3">PRD: Shenzhen, Jiangmen, Zhongshan, Huizhou;
YRD: Zhejiang Province (except for Huzhou, Zhoushan), Jiangsu Province (Changzhou, Suzhou, Nantong, Taizhou), Shanghai</td></tr>
<tr><td>Key sector</td><td colspan="3">Urban environments
Related services: Pollination</td></tr>
<tr><th colspan="2">EbA strategies</th><th>Possible benefits from strategies</th><th>References</th></tr>
<tr><td colspan="2">Enhanced vegetation (ornamental plants) at urban roadsides; protection for pollinators and their habitats</td><td>Food security; income benefits; biodiversity enhancement; risk reduction</td><td>(Dietzel et al., 2023; Gonzalez et al., 2021; Haines-Young and Potschin, 2018)</td></tr>
<tr><td>Connect to current policy</td><td colspan="3">SDG 15 (life on land);
Global Biodiversity Framework: Target 11 (restore, maintain and enhance nature’s contributions to people, including pollination); Target 12 (increase the area, quality and connectivity of green spaces in urban and densely populated areas)

National Climate Change Adaptation Strategy 2035: scientifically plan the layout of urban green belts, green corridors, green wedges, and greenways, and improve systems of urban green spaces;
China National Biodiversity Conservation Strategy and Action Plan (2011-2030): strengthen biodiversity conservation in urban areas; improve urban ecosystems.</td></tr>
<tr><td>Priority/ effective zones</td><td colspan="3">PRD: Zhongshan, Shenzhen;
YRD: Jiangsu Province (except for Nanjing, Yangzhou, Zhenjiang), Shanghai;</td></tr>
<tr><td>Key sector</td><td colspan="3">Coastal/Terrestrial environments
Related services: Biodiversity</td></tr>
<tr><th colspan="2">EbA strategies</th><th>Possible benefits from strategies</th><th>References</th></tr>
<tr><td colspan="2">Restoration of coastal ecosystems: restore mangrove, saltmarshes, oyster and coral reefs;

Ensuring redundant preserved areas; protecting important species</td><td>Food security; income benefits; human well-being; risk reduction (floods, storms, erosion, etc)</td><td>(Buenafe et al., 2023; Chausson et al., 2020; Powell et al., 2019)</td></tr>
<tr><td>Connect to current policy</td><td colspan="3">Global Biodiversity Framework: Target 2 & 3 (emphasis on restoration of degraded ecosystems); Target 4 (emphasis on species conservation)</td></tr>
</table>

<table>
<tr><td></td><td colspan="3">National Climate Change Adaptation Strategy 2035: Strengthen biodiversity protection for the terrestrial ecosystem; strengthen the protection of typical ecosystems and the restoration of degraded ecosystems;
China National Biodiversity Conservation Strategy and Action Plan (2011-2030): designate priority areas for biodiversity protection;
Master Plan for Major Projects to Protect and Restore China's Major Ecosystems (2021–2035): implement the planning and construction of major projects for ecological protection and restoration (key ecological zones of the Yangtze River);
Marine Eco-Environmental Protection Planning (2021-2025): enhance protection of marine biodiversity and ecosystems; improve the near-shore environment and the resilience to climate change.</td></tr>
<tr><td>Priority/ effective zones</td><td colspan="3">PRD: Shenzhen, Zhongshan;
YRD: Shanghai, Jiangsu Province (except for Yangzhou, Zhenjiang, Yancheng)</td></tr>
<tr><td>Key sector</td><td colspan="3">Urban environments
Related services: Climate regulation; Natural hazard protection; Air quality regulation</td></tr>
<tr><td colspan="2">EbA strategies</td><td>Possible benefits from strategies</td><td>References</td></tr>
<tr><td colspan="2">Urban tree management: forest park</td><td>Human health; risk reduction</td><td>(McVittie et al., 2018)</td></tr>
<tr><td>Connect to current policy</td><td colspan="3">New Urban Agenda; SDG 3 (good health & well-being), 11 (sustainable cities & communities), & 15 (life on land)
National Climate Change Adaptation Strategy 2035: build a nature reserve classification system with national parks as the main body, nature reserves as the basis, and various natural parks as supplements.</td></tr>
<tr><td>Priority/ effective zones</td><td colspan="3">PRD: Shenzhen, Zhongshan, Jiangmen, Huizhou;
YRD: Shanghai, Zhejiang Province (except for Hangzhou); Jiangsu Province (except for Nanjing, Zhenjiang); Anhui Province (Wuhu)</td></tr>
<tr><td>Key sector</td><td colspan="3">Urban environments
Related services: Tourism; Recreation</td></tr>
<tr><td colspan="2">EbA strategies</td><td>Possible benefits from strategies</td><td>References</td></tr>
<tr><td colspan="2">Urban environments: green spaces (urban parks and woodlands); blue infrastructure</td><td>Human well-being; risk reduction; income benefits</td><td>(McVittie et al., 2018; Nesbitt et al., 2017)</td></tr>
<tr><td>Connect to current policy</td><td colspan="3">New Urban Agenda; SDG 3 (good health and well-being) & 11 (sustainable cities & communities)
National Climate Change Adaptation Strategy 2035: enrich types of urban parks; priority to nature-based solutions;
China National Biodiversity Conservation Strategy and Action Plan (2011-2030): strengthen biodiversity conservation in urban areas; improve urban ecosystems</td></tr>
<tr><td>Priority/ effective zones</td><td colspan="3">PRD: Guangzhou, Zhuhai, Jiangmen;
YRD: Anhui Province (Chizhou, Hefei, Wuhu, Ma'anshan, Tongling), Jiangsu Province (Nantong, Yangzhou, Zhenjiang, Taizhou), Zhejiang Province (Hangzhou, Wenzhou, Jinhua, Huzhou)</td></tr>
</table>

EbA strategies have been implemented globally with increasing supporting evidence (IPCC, 2022a). As illustrated in Table 4-2, mangrove restoration is an advocated EbA practice to reduce the risks from coastal erosion, flooding, and storm surges, while simultaneously enhancing biodiversity and other ecosystem services (Powell et al., 2019; Seddon et al., 2020). Individual EbA measures could produce diverse co-benefits in terms of ecosystem services (McVittie et al., 2018), as demonstrated by the ecosystem-based adaptation measures exemplified in Table 4-2. Agroforestry is seen as an effective EbA, providing economic benefits to farmers and also helping to deliver other key ecosystem services, including pollination, soil quality regulation and water retention (Vignola et al., 2015). Sustainable forest management not only builds higher biomass productivity (increased income) and carbon sinks, but also enhances water resource management and water purification (Kelly et al., 2016; Yousefpour et al., 2020). Moreover, natural flood risk management (river restoration) for water security has been shown to enhance ecosystem service delivery and social benefits, mainly in the form of increased cultural services (Vermaat et al., 2016).

With the global rise in EbA strategy adoption and empirical evidence of their effectiveness, it is also essential to explore additional aspects of ecosystem vulnerability. Ecosystem susceptibility and robustness indicate the degree to which ecosystems are damaged, degraded, and fragmented, or the ecosystem capacity to stabilize ecological functions, respectively, and many indicators are related to climate change and EbA (Shah et al., 2020). The applications of these indicators in the two frameworks had an important impact on the final vulnerability results, highlighting the importance of appropriate EbA measures at the right scales. In both deltas, in addition to the water quality and biodiversity already mentioned, wetland connectivity, the use of chemicals and fertilisers, government expenditure on environmental protection, and the percentage of nature reserves are key drivers. Additionally, in the PRD, the percentage of deforested areas, forest and river connectivity are of high importance. Thus, suitable EbA approaches may include the restoration of forests and wetlands, natural ecosystem conservation, and agroecological practices.

4.4 Discussion and outlook

4.4.1 Advantages of identifying EbA strategies from ecosystem services and risk assessments

Integrating ecosystem services analysis within vulnerability and risk assessments can make the development of EbA measures more effective. The selection and use of site-specific indicators to improve the accuracy of assessment results facilitates the identification of priority areas for DRR and CCA. Stakeholders' participation can help assign the weights for each risk component, and allows for additional adjustments according to priority development goals. Meanwhile, SES vulnerability integrates information from biophysical and socioeconomic contexts critical for understanding the coupled social-ecological systems, and allows environmental perspectives to be integrated into adaptation strategies. The selection of EbA approaches should be guided by the vulnerability assessment and through an integrated social-ecological lens (Lo, 2016). Analysis of ecosystem services related to natural hazards further recognizes the links between vulnerability and ecosystem health, and enables the identification of key drivers of ecosystem services to formulate EbA options. Ecosystem services management provides co-benefits for climate change mitigation and adaptation, biodiversity protection, and sustainable development, and their perception and quantification have become the basis of ecosystem-based management and risk-informed environmental decisions (Peng et al., 2023; Tran and Brown, 2019). This study applied the DELTA-ES-SES framework to integrate ecosystem services into risk and vulnerability assessments, summarized empirical evidence on regional and global EbA implementation, and incorporated EbA into broader policy frameworks for risk reduction and adaptation strategies. It addresses regional knowledge gaps in identifying feasible EbA options suitable for local conditions and resource allocation, and provides long-term monitoring tools for study areas and regions facing similar climate challenges. Linking to EbA Criteria and assessment framework (FEBA, 2017), this study directly addresses 4 criteria: reduce vulnerabilities, generate societal benefits, restore, maintain or improve ecosystem health, and is supported by policies at multiple levels.

The GDRI framework includes the representation of the coupled SES of the delta environments and has been a practical tool for risk assessments based on various environments and contexts. Conversely, the DELTA-ES-SES framework has more fully integrated the characteristics of ecosystem services to build a stronger basis for including ecosystem services in EbA, DRR and CCA programmes. The degradation or restoration of these key services affects vulnerability and risk, and risk assessments involving them can prompt greater recognition of the role of ecosystem services and provide more effective background information for relevant government agencies when formulating EbA measures. The new ecosystem service sub-component in DELTA-ES-SES framework introduces a new pathway from risk assessment to EbA for disaster risk reduction and climate change adaptation. In addition to identifying drivers of multi-hazard risk, both risk assessment frameworks can be adapted to monitor place-specific hazard configurations and spatial scales (Hagenlocher et al., 2018; Peng et al., 2023).

The two frameworks allow for regular assessments, helping to track both short-term and long-term changes and intervention effectiveness continuously. Analysing vulnerability and risk distribution over different periods can help to determine risk patterns and changes in study areas, which is crucial for understanding how policy interventions or environmental changes impact risk and vulnerability dynamics. For instance, temporal vulnerability and risk analysis can monitor the changing pattern and trend in the risk profiles following specific adaptation projects or land use changes. Meanwhile, by adjusting indicator inputs, the frameworks can simulate various environmental and socio-economic settings, which is essential for predicting future vulnerability and risk trends. Additionally, identifying vulnerability drivers and high-risk areas contributes to determining priority sectors and designing adaptation projects. For instance, the DELTA-ES-SES framework supports the development of EbA projects at smaller scales to involve the role of ecosystem services in adapting to climate change impacts. Policy- and decision-makers can also utilize detailed data and visualizations to observe the effects of these practices, allowing them to adjust adaptation plans accordingly through ongoing assessments. The tools can enhance the effectiveness of climate change-related policies and interventions.

4.4.2 Policy implications for the Pearl River Delta and the Yangtze River Delta

Comparison of the outputs of the two frameworks reveals the impact of context setting/indicator selection prioritization on vulnerability and risk levels. The southwest of PRD and northeast and southeast of YRD show a medium to high risk, mainly characterized by higher economic development levels, population and ecosystem exposure to multiple natural hazards in coastal areas, and higher vulnerability driven by key drivers of social and ecological systems. While the GDRI did not directly account for the incidence and intensity of natural hazards, that is, the hazard component in risk equation, future trends in risk are greatly affected by the variability and distribution of multiple hazardous events. The likelihood that natural hazard-prone regions are likely to face more intense and frequent events in the future, emphasizes the need to assess these extreme events, especially for regional study-level (Schwarz and Kuleshov, 2022; Tessler et al., 2015). Meanwhile, multi-dimensional vulnerability indicators have different impacts on vulnerability levels. The ecosystem services component in the DELTA-ES-SES framework inevitably strengthens consideration of ecosystem services and environmental dimensions. DELTA-ES-SES considers provisioning, regulation & maintenance, and cultural services in a targeted manner more conducive to proposing ecosystem-based adaptations and risk reduction measures.

The advantage of ecosystem services is that they can be linked with EbA, and are closely related to concepts such as natural capital, Eco-DRR, and sustainable urbanisation, as well as key provisions of corresponding international environmental conventions/policy agreements (Estrella et al., 2016; IPCC, 2022a). Section 4.3.4 sets out EbA recommendations for main ecosystem types (natural, agricultural, urban and coastal ecosystems) in the PRD and YRD. Building on China's existing EbA implementation, with established ecosystem-based intervention pilots across the country (Luo et al., 2023), national and regional climate change adaptation plans, and associated policy frameworks, we suggest the following approaches and action priorities for the study sites.

4.4.2.1 Water resources

The significant influence of water supply, retention and quality in our analysis are closely associated with SDG 6 & 13 and align with China's integrated management plan on water resources and key ecosystem protection and restoration and provincial-level climate adaptation plans (BEES, 2023; DEEA, 2022; DEEG, 2022; DEEJ, 2022; DRCZ and DEEZ, 2021), which contain provisions emphasizing the construction of water resource security systems, and policy goals are also reflected in improving urban water use efficiency and agricultural irrigation systems. Although the importance of natural restoration is mentioned, clear action guidance and restoration goals for it are lacking. Improvement projects for the water environment still rely on traditional hard infrastructure, such as building river courses to intercept sewage (MEE, 2021). A national assessment of climate change adaptation also suggested there is a need for further enhancement of measures related to ecological restoration in the water resources sector (Fu et al., 2021).

EbA approaches like the re-connection of channels, and restoration of natural river courses and riparian vegetation have contributed to reducing flooding damage, enhancing water security, and reversing environmental degradation (Seddon et al., 2020). In China, the restoration and protection of watersheds in Beijing and Qiantang River, and water purification project in Fuxian Lake, have been assessed as improved scenarios in EbA practices (Luo et al., 2023). Currently, only Shanghai is promoting ecological protection and management of river systems, with expected goals for river and lake connectivity and water quality for 2025 and 2035 (BEES, 2023). In addition to Shanghai, the improvement of water quality in other regions also deserves attention, especially Zhongshan, Foshan, Huizhou, and Zhuhai in the PRD, and cities such as Suzhou, Taizhou_J, and Hangzhou in the YRD are also candidates for carrying out regional pilot projects such as restoring river networks.

4.4.2.2 Coastal ecosystems

Restoration of mangroves, swamps, coral reefs and salt marshes to reduce wave height and energy has become an evidenced-based and significant potential approach to coastal defence and protection (Morris et al., 2018; Narayan et al., 2016; Powell et al., 2019). This aligns with the prominent emphasis on ecosystem restoration within both international and national policy frameworks. For example, the GBF sets one target to ensure that at least 30% of degraded terrestrial, inland water, coastal and marine ecosystem areas are effectively restored by 2030 (CBD, 2022). The National Climate Change Adaptation Strategy 2035 also emphasizes promoting the restoration of coastal ecosystems, with a clear goal of remediating and restoring coastal wetlands of approximately 50,000 hectares by 2035 (MEE, 2022). Mangrove conservation and restoration in Shenzhen (PRD), has led to sustainable integrated land-sea management resulting in an increase in biodiversity, carbon sequestration, climate regulation, and culture (Luo et al., 2023; Ren et al., 2011). Guangdong Province (including the PRD region) aims to finalize the restoration of 2,500 hectares of coastal mangroves by 2025 (DEEG, 2022). Beyond maintaining Shenzhen's role as a marine city pilot, Zhongshan, identified as a risk hotspot, could present a priority to serve as a key area in the restoration efforts of coastal ecosystems like mangroves and seagrass.

Within the YRD, Shanghai, Jiangsu and Zhejiang provinces have extensive coastlines, with significant progress in Shanghai and Zhejiang Province pertaining to the enhancement of the adaptive capacity of their coastal zones. Specifically, Shanghai, as a developed municipality, benefits from substantial funding, and technical and scientific support, contributing to its low vulnerability and risk levels. Its forthcoming initiatives encompass a series of pilot projects to restore coastal wetlands and coastlines, thereby continuously and steadily improving the environmental quality (BEES, 2023). While the coastal regions of Zhejiang Province exhibit comparatively medium to high hazard exposure and ecological vulnerability, there is an acknowledgement of the imperative to reduce vulnerability and enhance adaptive capability. This is manifested in the inclusion of cities such as Ningbo, Taizhou_Z, and Wenzhou as integral construction projects of the "14th Five-year plan for responding to Climate Change of Zhejiang Province" (DRCZ and DEEZ, 2021), aligning with the imperative for actions underscored by assessment findings. In contrast, Jiangsu Province's medium to high vulnerability and risk distribution (except for Yancheng) also reflects its urgency to reduce vulnerability and risks. Remarkably, regional authorities are diligently engaged in risk reduction and adaptation measures. For instance, Yancheng, despite being a city with high hazard exposure, exhibits a low vulnerability level, a result that reflects past efforts to position Yancheng as a focal for coastal ecological restoration projects. However, as described in its regional plan, the current challenge in Jiangsu lies in the pace of major institutional and scientific-technological innovations aimed at addressing climate change, which lags behind neighbouring provinces and cities (DEEJ, 2022). To address this, in addition to strengthening the ecological restoration of Yancheng, more integrated protection and restoration projects of typical coastal ecosystems can also be extended to other coastal areas, with particular emphasis on Nantong and Suzhou.

4.4.2.3 Emphasis on agriculture and forestry

Broad incorporation of agricultural EbA practices such as agroforestry and policy emphasis on agriculture and forestry management can allow for the provision of multiple benefits such as erosion reduction, food and water security, cultural practices (Waldron et al., 2017). Agricultural diversification and natural vegetation have lower evapotranspiration compared to afforestation projects, benefiting water resources, carbon storage and biodiversity (Cao et al., 2016; Frank et al., 2015). Current practices in China like the restoration of degraded ecosystems in the Helan Mountains and forest restoration projects in the Fuxian, Poyang and Qiantang have all reflected more balanced, greener and more integrated sustainable ecological development (Huang et al., 2012; Luo et al., 2023).

Agriculture and forestry are recognized as key sectors vulnerable to the impacts of climate change in the overarching adaptation strategy. Nonetheless, they are viewed as separate sectors, with their objectives and plans managed in isolation. Strategies to enhance the climate resilience of agroecosystems are centred on refining agricultural planting structures (the selection of improved crop varieties), fertilization practices, and agricultural irrigation technology, particularly in the adaptation strategy of Guangdong, Jiangsu, and Anhui provinces. Only the plan of Zhejiang Province outlines the promotion of farmland protective forest belts (DRCZ and DEEZ, 2021). Within the forest sector, emphasis is placed on diverse species selection and the establishment of nature reserves. Each region, in this regard, has established binding targets for increasing forest coverage (BEES, 2023; DEEA, 2022; DEEG, 2022; DEEJ, 2022; DRCZ and DEEZ, 2021). Agroforestry, as an integrated practice, presents immense potential for enhancing agricultural productivity and soil conditions, and contributing to climate change mitigation. Its development without sacrificing other ecosystems (such as wetlands) can be a longer-term adaptation and mitigation strategy (Seddon et al., 2019), especially in agriculture-dominated regions such as Zhaoqing and Huizhou in the PRD, and Jiangsu Province in the YRD. It is worth noting that the effectiveness of agroforestry depends on the local climate, and its implementation may encounter challenges in regions prone to drought (Blaser et al., 2018). For example, Anhui Province in the study area is more exposed to drought, and needs to be considered with great care when considering agroforestry initiatives.

4.4.3.4 Urban context

The results above indicate that cultural services have a significant impact on urban vulnerability, mainly manifested in urban green space and tourism. The EbA practices mentioned in the above paragraphs mostly have positive impacts on cultural services, especially from the protection of biodiversity. The eco-cultural tourism and cultural innovation activities are increasing rapidly. There are also negative perceptions that can result, such as forestry management (forest planting) (McVittie et al., 2018). For urban ecosystems, developing green and blue infrastructure such as urban forest parks and infiltration facilities are in line with the key proposals of the New Urban Agenda, SDG 3 & 11, and China National Biodiversity Conservation Strategy. The process of enriching urban park types and improving the urban green and blue infrastructure emphasizes scientific planning and systematic connection. Currently, both Shanghai and Jiangsu Province have well-defined urban green space plans, explicitly aiming to achieve a 40% green coverage rate within urban built-up areas (BEES, 2023; DEEJ, 2022). When carrying out the construction of climate-adaptive cities, it is necessary to explore the actual situations of infrastructure development in various regions. For example, Guangzhou in the PRD and part of Anhui Province in the Yangtze River Delta are both considered priority/effective areas, but their respective construction priorities should be different.

Both PRD and YRD are key regions for integrated development and have advantages in cross-sector and cross-regional cooperation and financial input, which are conducive to implementing EbA approaches and monitoring their effectiveness. It is worth noting that almost all effective EbA practices have mentioned the key role of site-specific design and diverse stakeholder involvement. These processes include the involvement of local and scientific knowledge, identification of co-benefits, stakeholder collaboration, and funding availability to inform EbA design, implementation, and ongoing monitoring (McVittie et al., 2018; Nalau et al., 2018; Seddon et al., 2020). Furthermore, under current EbA practices, significant gaps were identified in the capacity of ecosystems conservation, biodiversity and climate change adaptation, such as the spatial mismatch of nature reserves coverage and the needed species conservation (Ji et al., 2023). The regional distribution of EbA implementation needs further identification to improve protection efficiency.

4.4.3 Limitations and outlook

The risk assessment frameworks and selected indicators allowed capturing the underlying drivers of social and ecological risks, while allowing for further policy integration at global and national levels, identifying context-specific adaptation actions. Currently, the planning of the PRD and YRD is basically based on the basin or cross provinces as a unit. After fully considering the scale, policy context, and data availability of the study area, we mapped the multi-risk at the city level. The findings of city units can provide sufficient evidence for project formulation and provide feasible EbA implications. Although our study provides a relatively comprehensive picture of the overall risk profile of each delta, there are common limitations linked to indicator-based risk assessments: lack of high-resolution spatial data, uncertainty from proxy indicators, and insufficient incorporation of stakeholder judgement. Besides, while ecosystem services are integrated into the DELTA-ES-SES framework to link risk reduction strategies with EbA and other global policy agreements, quantifying ecosystem service indicators may introduce additional uncertainties. Nevertheless, when considering the selected indicator-based approach as a simplified model, the integration of ecosystem services enables a more holistic assessment that better reflects reality and supports more integrated decision-making. Meanwhile, only expert consultations were included in the study, and government sectors and local communities were not fully considered, who may have different views on indicator selection and risk identification. In a prior study in which expert weights were integrated into the DELTA-ES-SES framework (Peng et al., 2024a, also Chapter 3), the risk level distribution exhibited no significant differences when contrasted with the results of this study. More accurate and locally relevant data are needed to formulate smaller-scale EbA in the future, which can be supplemented by calling on the academic community and government at various levels to address data scarcity, improve transdisciplinary knowledge integration, and enhance the participation of local communities. Overall, the implemented risk frameworks can both be easily adjusted from the delta scale to the regional/community scale, social and ecological vulnerability indicators can also systematically assess and monitor the social and ecological benefits of adaptation projects separately, which can be used as tools for EbA construction process and follow-up monitoring.

4.5 Conclusion

This study applied two integrated risk assessment frameworks in the PRD and YRD, and established new pathways linking vulnerability indicators, EbA measures development and related provisions on key policies for improved ecosystem conservation, disaster risk and climate change mitigation, and sustainable development. This method allows the analysis of the contribution of each indicator to risk, which can be used to consider regions characterized by high levels in selected vulnerability indicators or risk as priority/effective zones for EbA implementation. The findings emphasize the consideration of different EbA practices in relation to regional ecosystem types, with specific examples provided. This study focuses on providing EbA recommendations for the two deltas from the perspective of key ecosystem services, further applications can be made to explore regional differences to help policymakers and practitioners meet local targets.

Methods based on the integrated SES theoretical framework and indicator list are both easily adaptable and applicable globally. Additionally, this approach may incorporate more local indicators with quantitative/qualitative data. The practicality of these risk frameworks is their capacity to quantify and visualize the social and ecological dimensions of risk components, in particular the DELTA-ES-SES framework considering ecosystem services, contributing targeted EbA measures to address the climate crisis.

5. Conclusion

This study explored the role of ecosystem services in the context of risk analysis for natural hazards, aiming to better represent SES dynamics and enhance the assessment of vulnerability and risk of coupled deltaic SES. Additionally, the research both compared the extent and distribution of risk within and between two coastal river deltas and suggested ecosystem-based adaptation options tailored to the study sites, thereby improving their capacity for disaster risk reduction and climate change adaptation. This work has highlighted the relationship between ecosystem services and interconnected social and ecological sub-systems, emphasizing their role in complementing aspects of social and ecosystem vulnerability — a crucial understanding for comprehensive and balanced vulnerability analysis of SES. This chapter follows the outlined process (Fig. 5-1), first addressing the three main research questions presented in Section 1.4 by synthesizing the findings from Chapters 2, 3 and 4. Subsequently, by taking the three papers together, the conclusion outlines the contributions of this study in terms of conceptual framework development and empirical findings, along with existing limitations and prospects for future work.

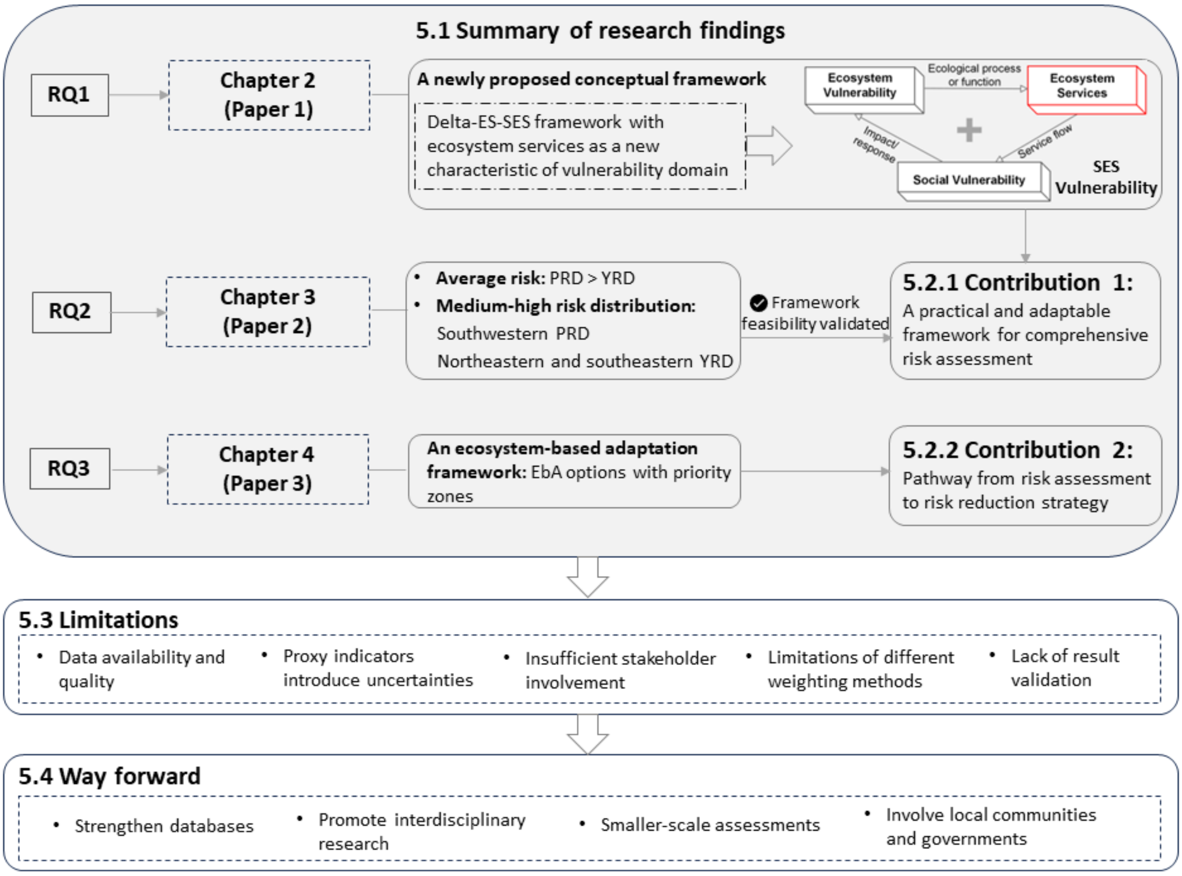


Figure 5-1 Structure and workflow of the conclusion. Each subsection's key elements are depicted individually.

5.1 Summary of research findings

In this section, the synthesis of findings from Chapters 2, 3, and 4 addresses three research questions.

RQ1. How can we best integrate ecosystem services into SES vulnerability and risk assessment to improve current vulnerability and risk assessment approaches?

In response to insufficient consideration of ecological dimension in representing social-ecological systems in prior risk assessments, ecosystem services, encompassing cross-scale ecological and social processes, were integrated as sub-components in the vulnerability domain of a risk assessment framework. This addressed a gap in SES vulnerability research on underrepresented ecosystem vulnerability and how to link biophysical and social aspects. Chapter 1 has described in detail the concepts, theories and practices of vulnerability and risk analysis, establishing the groundwork for this research. Chapter 2 (Paper 1) highlighted the importance of incorporating elements from both natural and social systems, thereby complementing existing social and ecosystem vulnerability indicators.

The integration of ecosystem services necessitates the convergence of two research fields: vulnerability of social-ecological systems and ecosystem services research. This combination aims to meet the overall goal of conducting a more comprehensive vulnerability and risk assessment in deltaic environments exposed to multiple natural hazards. The starting point was the Delta-SES framework proposed by Sebesvari et al. (2016), which comprehensively encompasses both ecological and social dimensions of vulnerability, incorporating their essential characteristics. Within this framework, ecosystem vulnerability is comprised of ecosystem susceptibility, ecosystem robustness, and social vulnerability encompasses social susceptibility, coping, and adaptive capacity. This modular and relatively comprehensive framework provides an adequate foundation for incorporating a new ecosystem service sub-component. Nonetheless, there remains a need to discuss how to contextualize ecosystem services within the structure of SES vulnerability, elucidating their relevance with ecosystem and social vulnerability. To address this, I highlight the need to provide a detailed description of the structure and practicality of the newly proposed conceptual framework (Delta-ES-SES).

The proposed Delta-ES-SES framework emphasises ecosystem services as a new characteristic of the vulnerability of socio-ecological systems to address RQ1, depicted in the simplified version of vulnerability component in the upper-right of Fig. 5-1. The dynamics of ecosystem services simultaneously demonstrate the intricate interactions and feedback between social and ecological sub-systems. To achieve this, I drew the connection between ecosystem vulnerability, ecosystem services and social vulnerability through the SES vulnerability cascade model. Additionally, I summarized vulnerability indicators related to ecosystem services, derived from both biophysical processes or ecological functions and social contexts. In summary, the Delta-ES-SES framework mainly includes the following elements and characteristics:

1) Risk is viewed as a product of hazard, exposure and vulnerability components. When (multi-) hazardous events occur, their influence on elements of the social-ecological systems may cause adverse interactions or effects, thereby constituting the risk.

2) It captures multiple hazards affecting socio-ecological systems at different spatial scales. It allows assessing the severity of the hazard component by considering the magnitude, duration, and probability of occurrence of multiple hazards. The exposure component primarily encompasses the extent to which critical elements of the social-ecological system (economy, population, and ecosystems) might be adversely affected.

3) Within this framework, vulnerability encompasses three sub-components: social vulnerability, ecosystem vulnerability, and ecosystem services. Specifically, social vulnerability comprises social susceptibility (indicators tied to key services and demographic characteristics), coping capacity (individual and household characteristics, infrastructure and services), and adaptive capacity (social and institutional adaptation). Ecosystem vulnerability encompasses ecosystem susceptibility (indicators related to habitat destruction, degradation, and fragmentation) and ecosystem robustness (indicators reflecting ecosystem protection and restoration).

   Ecosystem services serve as a representation of ecosystems' capacity to support human society. They are understood as ecological elements or processes related to social outcomes to be adversely affected when exposed to multiple hazards, their predisposition could reflect the vulnerability characteristics of social-ecological systems. Framing ecosystem services in this way enhances the evaluation of critical ecological processes directly linked to human well-being. The historical evolution of ecosystem services research has established both the theoretical and practical foundation for environmental assessment and management.

This modular structure facilitates the incorporation of indicators to guide vulnerability assessments. Integrating various aspects into vulnerability, including demographics, socioeconomics and ecosystem characteristics, holds the potential to formulate integrated disaster risk reduction and climate change adaptation strategies for future management.

4) The interactions within social-ecological systems are dynamic processes across spatial and temporal scales, involving various ecological processes, the delivery of ecosystem services, and the influence of human activities on the environment. Overall vulnerability is shaped by the combination of ecological processes and social impacts across various scales, from within and outside the delta. In the context of given environments for vulnerability analysis, considerations should extend to ecological and social sub-systems at various spatial scales, incorporating specific administrative units and land use/land cover as fundamental elements for configuring hazards and selecting indicators in case studies.

RQ2. What are the general vulnerability and risk profiles in China's two major deltas (Pearl River and Yangtze River deltas) when exposed to multiple natural hazards?

The Delta-ES-SES framework has defined the working structure and essential elements for vulnerability and risk assessment in delta environments. Following the research design described in Section 3.2, Chapter 3 (Paper 2) applied the methodology outlined in Chapter 2, combining expert consultation, available multi-source indicator data, and data processing procedures, to conduct risk assessments in the PRD and YRD. The construction of the risk index involved the aggregation of normalized and weighted scores, with the main workflow depicted in Fig. 3-3. Taking into account the varying scales and sources of indicator data, as well as the administrative units involved in integrated risk management in the deltas, all data are scaled to the city level. The final multi-hazard risk index incorporates five natural hazards, exposure of economic activities, population and ecosystems, along with 57 vulnerability indicators of three main vulnerability domains. Compared with previous studies, it has added more consideration of environmental indicators and reflected a more comprehensive analysis of the vulnerability of deltaic social-ecological systems.

The case studies not only validate the feasibility of the Delta-ES-SES framework, but also draw the vulnerability and risk profiles for both deltas, addressing RQ2. The comparative analysis of risk scores between the two deltas indicates that the average risk in the PRD is higher than in the YRD. The case study includes delta- and city-level risk assessments that identify regions within the study area characterized by higher incidence of natural hazards, higher economic/demographic/ecosystem exposure, vulnerability, and final multi-hazard risk. From the perspective of spatial distribution, the southwestern PRD, northeastern and southeastern YRD present medium to high risk levels.

Separate analyses of risk, hazard*exposure, and vulnerability have further revealed internal differences in the scores of different sub-components within the two deltas. For example, while some cities exhibit similar risk levels, there are differences in vulnerability scores. Fig. 5-2 illustrates a simplified comparative depiction of spatial distribution of risk components and final risk level. Examining the spatial distribution of risk sub-components, the observed convergence in risk levels and hazard*exposure scores implies that differences in risk level are significantly related to the intensity and frequency of hazard events. Meanwhile, the decomposition of hazard components shows that although both study areas belong to coastal river deltas, they are severely affected by different types of natural hazards. The PRD region faces high-intensity cyclones and storm surges, while the YRD region is more exposed to drought.

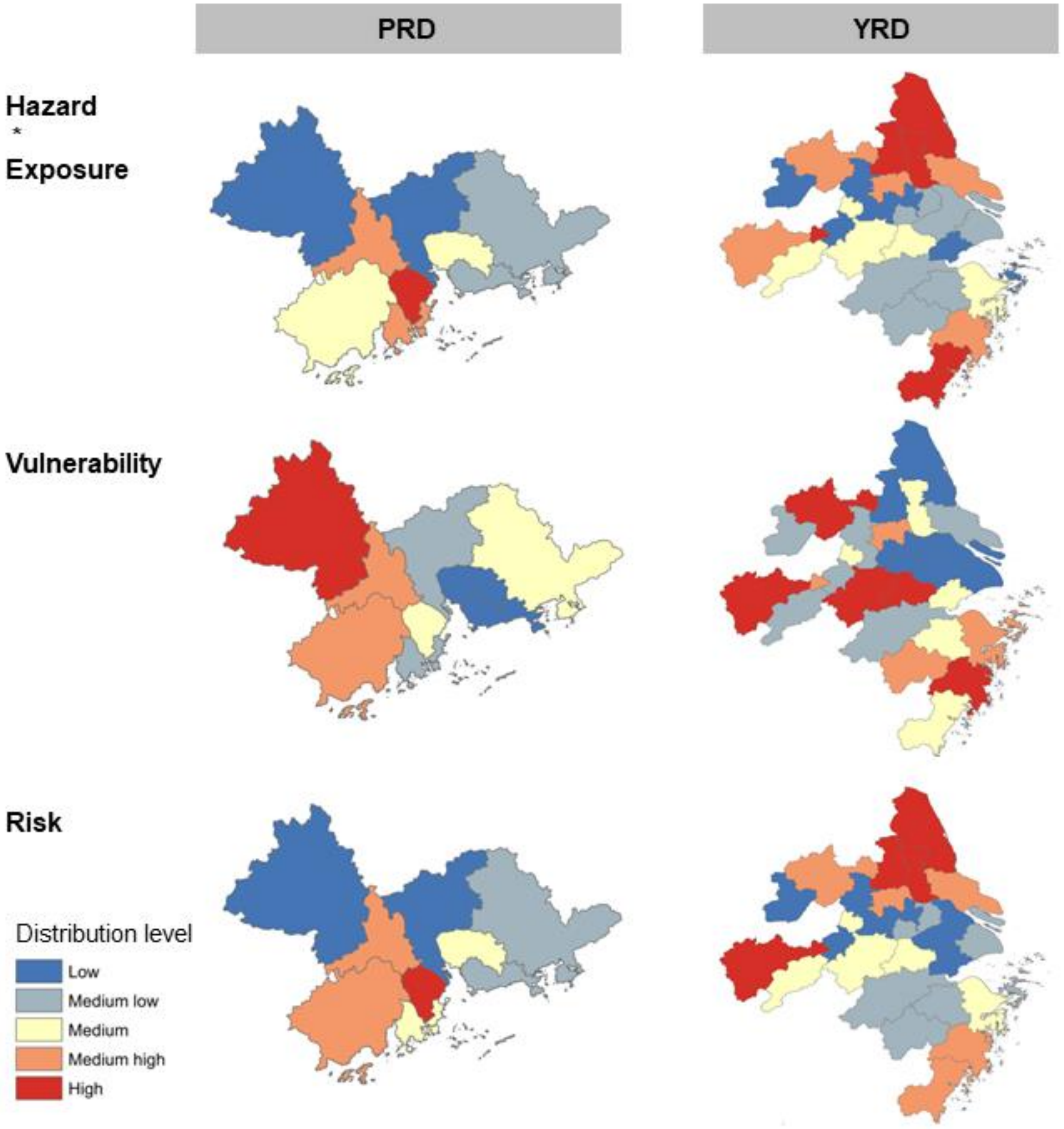


Figure 5-2 Spatial distribution of risk components and final risk level of Pearl River Delta (PRD) and Yangtze River Delta (YRD). Note: The scales between deltas are not comparable for better visualization. See Chapter 3 for details.

The relative contribution of vulnerability indicators to risk score varies across study areas, and their impact on vulnerability sub-components differs as well. The inclusion of the newly added ecosystem services component allows a more comprehensive understanding of ecosystem health and its capacity to provide services linked to SES vulnerability. For example, the data in Chapter 3 show the key role of water provisioning and water quality regulation, reflecting the high dependence of delta sustainable development on water-related ecosystem services. This implies the potential for linking risk assessment to risk reduction strategies and water resource management policies. These analyses serve as a prerequisite for formulating targeted and effective DRR strategies.

RQ3. What effective adaptation measures could be proposed when considering the role of ecosystem services to reduce vulnerability and risk in the future?

Methodological advances made in vulnerability and risk assessment for deltas can also be extended to adaptation measures and policy implications. Chapter 4 (Paper 3) has further applied the widely used risk assessment framework (GDRI) and the newly developed risk assessment framework (DELTA-ES-SES) in the two river deltas. The aim was to compare the impact of differences in risk components on regional vulnerability and risk distribution, with a focus on the role of ecosystem services. Chapter 4 proposed an ecosystem-based adaptation framework aimed at addressing DRR and CCA. Unlike previous applications of existing risk assessment frameworks, this study directly links key drivers of SES vulnerability and risk to DRR and CCA strategies. The concept of EbA has gained wide attention in addressing climate-related disasters and climate change impacts, due to its potential synergies and co-benefits. EbA emphasizes the importance of ecosystem integrity and the various ecosystem services. The application of the DELTA-ES-SES framework not only identifies key ecosystem services but also provides evidence-based information for DRR measures based on ecosystem service indicators. This is consistent with the processes of EbA planning and implementation.

Chapter 4 starts with a regional vulnerability and risk assessment, and moves to the analysis of individual vulnerability components for each city. Understanding the statistical relationship between ecosystem service indicators and vulnerability scores is critical for identifying key drivers affecting risk and formulating targeted policy suggestions for priority sectors and zones. When proposing adaptation strategies based on ecosystem services, areas where these services exhibit a relatively greater impact on vulnerability can be identified as priority/effective zones. Furthermore, ecosystem vulnerability indicators also have an important impact on the final vulnerability results, and provide information for further determining appropriate spatial scales when proposing and implementing EbA measures. For example, the percentage of deforested areas, forest connectivity, and river connectivity are important factors of ecosystem vulnerability in the PRD region, which can be linked to EbA approaches such as forest and wetland restoration. Addressing RQ3, Table 4-2 (section 4.3.4) combines key ecosystem services with multi-dimensional policy goals to list EbA recommendations and priority/effective areas for their implementation in the study areas.

Chapter 4 links ecosystem services and environmental issues to the integration of global and national policies such as the SFDRR, the SDGs, the Global Biodiversity Framework, and

National Climate Change Adaptation Strategy 2035 in China. The EbA options provided are consistent with the objectives of relevant policies and strategies at the national and global levels reviewed, and provide more effective background information for decision-makers involved in the formulation of EbA measures and future plans.

5.2 Contributions of this research

5.2.1 A practical and adaptable framework for comprehensive risk assessment

The Delta-ES-SES framework, introduced in Chapter 2, subdivides multi-hazard risk into hierarchy-based modules and provides a comprehensive set of indicators covering vulnerability and risk factors across nature, environment, economy, and policy domains for practical application. It significantly clarified (multi-)hazard risk components and supports single-hazard analysis as well as visualization of different sub-components. After a literature review of ecosystem services research in delta/coastal environments, the SES vulnerability cascade framework (Fig. 2-5) was applied to identify linkages between ecosystem services, ecosystem vulnerability and social vulnerability. Traditional risk assessments did not adequately consider the critical role that ecosystem services play in supporting SES resilience, reducing vulnerability and risks, and buffering against climate change impacts. This approach provides potential ecosystem service indicators associated with SES vulnerability, advances a holistic approach to understanding the interconnectedness of complex SESs, and can be used to support future research.

The indicator-based assessment method not only facilitates the construction of composite indicators for quantifying risk, but also allows for increased detail (e.g. incorporating additional indicators) or reduced complexity, depending on research goals. It demonstrates high adjustability and transferability, making it particularly suitable for comparative research and large-scale studies. Moreover, selected indicators can be assigned weights according to environmental settings and research priorities, allowing adaptation to regional development goals, with a wide range of applications. This approach enables the combination of quantitative and qualitative methods, enhancing the integration of local knowledge and providing a broader perspective for risk analysis. It supports collaboration with academic, government sectors, and local communities in interdisciplinary, cross-sector and cross-scale research to provide actionable information to decision-makers and promote localized risk management. The DELTA-ES-SES framework and combined indicator library support ongoing assessments to track changing risk profiles and predict future trends in the selected areas. It not only enables risk assessment at various spatial and temporal scales in deltaic environments but can also allow for global applicability with adjustable indicators. This facilitates comparative studies at various scales, enabling researchers to identify, summarize, and exchange about the effectiveness of risk reduction measures.

Chapter 3 and Chapter 4 both applied the Delta-ES-SES framework, integrating regional knowledge through expert consultation and utilizing available data for risk assessments in the PRD and YRD, addressing research questions 2 & 3. Additionally, Chapter 4 compared the risk assessment results of the DELTA-ES-SES framework with the widely used GDRI framework in the PRD and YRD. There is good spatial overlap with only 17% (6/36 cities) showing above one level difference in risk distribution, while vulnerability level comparison has even fewer differences. Both Chapter 3 and Chapter 4 examined the feasibility of the selected approach. This study is unique in its endeavour to perform the risk assessment within a newly developed SES framework with the role of ecosystem services, primarily due to prior studies not fully incorporating the ecological dimensions of vulnerability. While the importance of ecosystem services in risk reduction is determined, previous risk assessment frameworks or applications have not fully considered their role. DELTA-ES-SES incorporates ecosystem service indicators into the practice of vulnerability analysis, offering a more comprehensive understanding of multi-dimensional vulnerability. Meanwhile, the ecosystem service component holds substantial potential in designing and implementing strategies for EbA, DRR, and CCA.

As highlighted in Chapter 3, there remained a lack of multi-hazard risk assessment for the PRD and YRD. In particular, current risk assessments of the YRD have not covered a total of 27 cities defined in the Outline of the Yangtze River Delta Regional Integrated Development Plan. Chapters 3 and 4 map the risk distribution of the PRD and YRD under expert weights and equal weights respectively, showing no big risk difference. Comparing research findings with other risk assessments also demonstrates consistency, for instance, a high-risk level in the southeastern YRD. Moreover, this approach supports the examination of internal differences or drivers in risk distribution across these cities to inform future integrated risk planning and wider management practices.

5.2.2 Pathway from risk assessment to risk reduction strategy

Global agreements such as the Paris Agreement and SFDRR have urged the scientific community to develop a comprehensive understanding of the intricate nature of disaster risks, that is, to understand all aspects of risk and risk components (UNDRR, 2015; UNFCCC, 2015). This study provides a comprehensive perspective on the multi-hazard risk profiles in the PRD and YRD regions. The findings from Chapters 3 and 4 can be used to advance the delta-based, provincial and city-level DRR practices. The identification of high-risk areas, such as Zhongshan and Foshan in the PRD, Taizhou_J and Yangzhou in the YRD, highlights the urgency of formulating and implementing effective DRR strategies in these regions. The analysis further revealed inconsistencies between risk levels and underlying vulnerabilities, providing crucial information to guide decision-makers in proposing DRR measures. For example, although Yancheng is highly exposed to multiple hazards, its vulnerability level is relatively low. Regional policy goals and practices demonstrate the local government's commitment to positioning Yancheng as a key area for comprehensive protection and restoration projects of coastal ecosystems (DEEJ, 2022). This reflects the effectiveness of local authorities' efforts in adopting risk reduction and adaptation measures.

The breakdown analysis of vulnerability (Fig. 3-8) reveals the varied impacts of vulnerability sub-components on different regions, and determines the sources of high vulnerability in each region. Although some social indicators (such as GDP per capita) representing economic conditions directly, may pose challenges for rapid improvement, targeted plans/actions in key infrastructure sectors can offer short-term enhancement possibilities. For instance, indicators like the "number of hospital beds per 1,000 residents" and "public health expenditure" play critical roles in affecting the coping capacity of the PRD region. Improving the medical system, therefore, emerges as a strategy for enhancing the PRD's capacity to address future risks. Regarding the YRD, its spatial pattern across multiple provinces results in disparities in socio-economic conditions. Anhui Province exhibits higher levels of social susceptibility and lack of coping and adaptive capacity compared to Shanghai, Jiangsu, and Zhejiang provinces. Implementing targeted management measures in Anhui Province to reduce social vulnerability holds the potential for achieving greater results.

This study uniquely integrates the concept of ecosystem services into vulnerability and risk assessment, facilitating the formulation of ecosystem-based measures like EbA for DRR. Although prior methods and studies also contribute to identifying risk or vulnerability drivers, such as the aforementioned key factors of social vulnerability, this study advances by supporting the extraction of vulnerability drivers from ecosystem service indicators in risk assessments. This approach optimally provides environmental dimension information for developing ecosystem-based DRR strategies. Chapter 4, in its vulnerability analysis of 36 cities in two deltas, proposes a series of EbA recommendations for key sectors and ecosystems, namely water resources, agroforestry, coastal, and urban environments. Meanwhile, the ecosystem vulnerability component identifies ecological factors beyond ecosystem services, such as wetland connectivity in the two deltas, promoting the implementation of EbA measures like the restoration of wetland ecosystems. Risk assessments should encompass decisions across all government levels and their implications for DRR strategies. There is currently a gap in resource allocation (e.g. funds) for addressing disaster risks and climate change impacts among different regions, cities, and communities (Kruczkiewicz et al., 2021), such as between Shanghai and Anhui in the YRD. Following a comprehensive analysis of international and national policy frameworks related to DRR and CCA, coupled with China's EbA implementation progress, Chapter 4 provides suggestions for priority areas/sectors and policy development for future EbA implementation in the study area.

Risk assessment using the Delta-ES-SES framework not only addresses Steps A&B (understanding SES, assessing vulnerabilities and risks) in the stepwise approach developed by CBD (2019) for the design and effective implementation of ecosystem-based approaches; it also simultaneously contributes to Steps C&D (identifying, prioritizing, appraising, and selecting EbA options). This integrated approach can simplify the procedures of developing EbA strategies, and maintain consistent information from risk identification to risk reduction rather than separate studies. This holistic perspective not only addresses current research gaps in understanding and monitoring the effectiveness of EbA practices but also aligns with global and regional policy frameworks emphasizing EbA for DRR, CCA, and sustainable development. It allows researchers to assess how specific ecosystem services contribute to disaster risk reduction and develop targeted strategies for identified priority zones. The Delta-ES-SES framework supports research across various spatial scales, from cities to counties or communities, and allows for the consideration of various ecosystem types. This brings more possibilities when formulating EbA measures, including supporting procedures for comparative assessment and involving multiple stakeholders in determining priority targets at the community level.

Overall, this study's analysis of SES vulnerability synthesizes extensive information from biophysical, environmental and socioeconomic contexts. The insights provided not only support social sectors (hard infrastructure construction), but also advocate for enhancing adaptive capacity through ecological dimensions (e.g., EbA, Eco-DRR, and NBS options). In combining risk assessment methods with widely recognized EbA approaches, I emphasize further improving the accuracy of planning projects and providing more local knowledge at the regional level. Integrating risk assessment methods with widely recognized EbA approaches highlights the need to further provide more local knowledge at the regional level and improve the accuracy of planning projects.

5.3 Limitations

While mapping the risk profiles of PRD and YRD contributes to proposing disaster risk reduction measures, several analytical limitations need to be acknowledged. The first is the inherent limitations of the conceptual framework in practice. Despite the conceptual framework capturing SES interactions across spatial scales, identifying specific coupling dynamics remains challenging in risk assessment. The inclusion of ecosystem services as a component enhances consideration of SES interactions. However, a new challenge arises from the availability of indicator data for ecosystems and their services. Depending on the research scale, ecosystem services research often relies on system modelling (Li et al., 2022; Pu et al., 2023), and participatory methods such as stakeholders' perceptions (Langemeyer et al., 2018; Shakya et al., 2021). Given the study's focus on comparing the risks of the two deltas and identifying hotspots as targets for subsequent risk management, challenges arise in assessing ecosystem services within the context of social-ecological vulnerability. Due to the expansive scale of the deltas, this study could not involve a broad range and large number of local stakeholders; instead, relevant knowledge was obtained through expert consultation and existing research. Sources of ecosystem service indicator data are based on relevant research and public data. Some indicators use simplified proxy indicators (e.g., using agricultural production to represent biomass from cultivated terrestrial plants), introducing inevitable uncertainties. Incorporating broader stakeholder perceptions of ecosystem services could potentially change the results.

Likewise, indicator-based assessment methods face difficulties assessing interrelationships between indicators across regions, such as the impact of management measures taken by one city on the vulnerability levels of neighbouring cities. This static assessment approach represents an unavoidable compromise between the intricate representation of reality and the practicality required in risk assessment (Anderson et al., 2021). Indeed, constructing a comprehensive risk indicator is, in essence, a simplification of reality. Hence, utilizing risk scores should involve considering other subcomponents and their indicators to draw complex policy conclusions (Marin-Ferrer et al., 2017). Data availability and quality pose significant challenges for an indicator-based approach (Maini et al., 2017). While multiple indicators bring more information, data from various sources, years, and spatial scales impact the accuracy of the final results. Meanwhile, to maintain the consistency of indicator data, this study did not address the uncertainty introduced by the COVID-19 pandemic, particularly its influence on indicators related to socioeconomic activities (e.g., economic exposure, per capita GDP). Despite the Delta-ES-SES framework supporting spatially explicit methods, the ultimate analysis is based on the city level due to the lack of spatially explicit grid data for certain indicators. Although city-level risk assessments align with the goals of integrated planning policies, they cannot capture regional vulnerability and risk variations at smaller levels, such as urban-rural differences. The heterogeneous distribution of ecosystem types implies potentially significant differences in the supply of ecosystem services within and between urban and rural areas. Additionally, the role of remote sensing and hydrological models is critical in hazard identification and data collection, particularly in data-scarce regions. For example, some hazards like harmful algal blooms (red tide in PRD and YRD) are recognized as important but cannot be considered in the multiple hazards due to a lack of spatially explicit data. Consequently, improving the availability and accuracy of the data is imperative.

Furthermore, in Chapter 3, expert weights were utilized, potentially influencing the relative contribution of risk sub-components and their respective indicators to risk levels. Although endeavours were made to engage experts from various fields to gain more relevant knowledge, this approach introduces a degree of uncertainty due to potential misunderstandings regarding experts' perceptions of risk and its components. However, it is noteworthy that, in this study, different weighting methods appear to have only a small impact. A comparison with results using equal weights reveals small differences in the final risk distribution. Furthermore, this study exclusively involved expert consultation and did not fully consider other stakeholders, such as government departments and local communities. These stakeholders may possess different perspectives on indicator selection and weight assignments.

Both weighting tools, AHP and IAHP, exhibit limitations. AHP, widely utilized in risk assessment, presents significant challenges for participants, being time-consuming and prone to inconsistent judgments. When using the AHP method to construct a pairwise comparison matrix for the relative importance ranking of indicators provided by experts, only a consistency ratio below 0.10 is acceptable, necessitating the exclusion of unsatisfactory data. IAHP is suitable for the importance ranking of multiple indicators, involving sorting indicators and assigning values through linear interpolation, allowing it to pass the consistency test. However, subjective sorting inherently introduces additional arbitrariness. These considerations emphasize the need to evaluate and select an appropriate weighting method based on environment-specific relevance and the number of indicators.

Finally, the vulnerability results of this study lack validation due to the unavailability of damage data to represent vulnerability. Whether on social or ecosystem vulnerability, the integration of multiple dimensions within the two subsystems makes it challenging to characterize using proxy indicators. One possibility for validation is comparing the risk distribution with historical disaster data published by the government, but the lack of spatial data remains a significant issue. Nonetheless, some matches can be found by comparing the results with findings from other studies. As discussed in Chapter 3, the PRD region and the Zhejiang Province of the YRD face high-risk levels of cyclones, aligning with two separate assessments of typhoon risk in China (Sajjad et al., 2020; Yin et al., 2013).

5.4 Outlook and way forward

This thesis presents an SES-based multi-hazard risk assessment framework and tools to communicate risks effectively to policymakers and the wider community, emphasizing the need for improved risk assessments to facilitate disaster risk management. To deepen the understanding of disaster risk and promote the sustainable management of SES, it is crucial to identify multi-dimensional drivers of SES vulnerability and conduct vulnerability and risk assessments. In light of evolving methodologies, future research should improve the accuracy of risk assessments in determining and predicting potential risks. Technically, there is great potential to integrate the dynamics of vulnerability into risk assessments. Vulnerability, as the propensity of SES elements to be adversely affected by multiple hazards, is characterized by temporal and spatial dynamics (de Ruiter et al., 2020). Extreme climate-related events can exacerbate an adverse cycle of physical, social and economic vulnerability (Reichstein et al., 2021). For example, flooding-induced destruction of infrastructure and crops weakens societal, household, and individual capacities to address risks, leading to higher poverty levels and potentially increasing future vulnerability (Kruczkiewicz et al., 2021). This complexity across different systems remains challenging to quantify directly and is inadequately considered in current practices (de Ruiter and van Loon, 2022; Hagenlocher et al., 2019). This is because capturing the temporal and spatial dynamics of vulnerability relies on the availability of suitable data for the indicator construction process. With improved data quality and availability, consecutive risk assessments can consider spatiotemporal dynamics and hazard interactions (de Ruiter et al., 2020). Governments at all levels are thus urged to enhance existing databases and bolster interdisciplinary knowledge integration to foster a comprehensive understanding of vulnerability dynamics and the development of assessment methodologies.

Regions highly exposed to hazardous events may anticipate a heightened frequency of occurrences in the future, highlighting the importance of analysing the trend of such events (Schwarz and Kuleshov, 2022). Existing research has diligently addressed the modelling, monitoring, and prediction of hazard components, although temporal and spatial resolutions are limited, spatially explicit datasets serve as a foundation for interdisciplinary research (Formetta and Feyen, 2019). A thorough analysis of the spatiotemporal dynamics of risk and vulnerability could further capture the interactions between strategies such as risk reduction and climate adaptation (Simpson et al., 2021). Comprehensive risk assessment methods rely on the integration of interdisciplinary knowledge, involving research on natural hazards and the drivers of vulnerability and exposure components, while promoting the transfer of scientific knowledge from research to practice (Cutter et al., 2015).

This study aimed to provide supporting information for decision-makers in formulating disaster risk reduction and climate change adaptation strategies in the PRD and YRD. Future research should shift its focus towards smaller spatial scale assessments, a limitation in this study due to time, funding, and data availability constraints. As mentioned above, areas severely affected by climate-related hazards are expected to experience more recurrent and intense extreme events, heightening the likelihood of interactions between multiple hazards (de Ruiter et al., 2020). Consequently, the identified risk hotspot areas can serve as priority zones for further in-depth risk analysis. The involvement of participants, including experts, local communities, regional authorities, and other stakeholders, is crucial for the further development and application of the proposed framework. Experts play a key role in refining the selection and weighting of indicators, improving methodologies, and identifying gaps in the study areas for further study. Given that DDR actions tend to be localized, with some practices targeting specific community levels, emphasizes the importance of collaborative follow-up research involving local communities and governments. Future development of smaller-scale EbA or other DRR measures requires more accurate and locally relevant data. Hence, the wide range of participants can contribute to providing local knowledge and data, feedback on perceived conditions, and validation of research findings. While this study identified risk hotspots at the city level, the subsequent phase involves narrowing down the focus to counties/villages or even the community level. Conducting smaller-scale risk assessments not only facilitates broader stakeholder inclusion but also enhances data availability with more qualitative data obtained from participatory methods, particularly for ecosystem indicators in data-scarce scenarios. Participatory feedback also enhances the framework and its indicator library, ensuring they adjust to changing realities. Extensive engagement with decision-makers and stakeholders can additionally promote effective communication and community acceptance of decisions, thereby enhancing the implementation of management strategies.

Appendices

Appendix 1. Overview of main ecosystem services (Chapter 2)

Appendix 2. Overview of main interlinkages between three main vulnerability domains (Chapter 2)

Appendix 3. List of vulnerability and risk assessment indicators (Chapter 2)

Appendix 4. List of the reviewed papers (Chapter 2)

Appendix 5. Indicators selection questionnaire (Chapter 3)

Appendix 6. Weights selection questionnaire (Chapter 3)

Appendix 7. Data sources (Chapter 3)

Appendix 8. Data processing (Chapter 3)

Appendix 9. Supplementary material of Chapter 4

Appendix 10 Additional material: conceptual framework and risk index structure

Appendix 1 - 3 are available in https://doi.org/10.1016/j.jenvman.2022.116682

Appendix 7 - 8 can be found in https://doi.org/10.1016/j.ocecoaman.2023.106980

Appendix 1 Overview of main ecosystem services (Chapter 2)

Appendix 1 provides example indicators of ecosystem services that can be used for vulnerability and risk assessment.

The ecosystem service divisions mentioned in the 17 reviewed papers are shown on the left side of the table below. The table indicates the categories of ecosystem services in relation to different ecosystems types. There are relatively few studies that consider ecosystem services when conducting vulnerability or risk assessments in deltas or coastal areas. In some cases, studies did not address natural hazards, but the ecosystem services mentioned were related to the social-ecological systems of the delta or coastal areas. The included ecosystem services are all considered relevant to this research. In addition, the table below combines CICES V5.1 and practical study introduced in the CICES V5.1 Guidance to provide example indicators for each ecosystem service division. These indicators are mainly used for the development of ecosystem service indicators in the subsequent analysis of vulnerability and risk.

CICES Division	**Aquatic ecosystem**	**Aquaculture ecosystem**	**Terrestrial ecosystem**	**Agroecosystem**	**References**	**Flooding**	**Storm surge**	**References**	**CICES Class**	**Example indicators**	**References**
	Ecosystem types					**Hazard types**					
Provisioning											
Biomass: food	√	√	√	√	(Asmus et al., 2019; Chung et al., 2015;	√		(Mansur et al., 2016)	Cultivated terrestrial plants for nutrition, materials or energy	Primary production	(Depellegrin et al., 2020; Mansur et al., 2016)

					Depellegrin et al., 2020; Mansur et al., 2016; Mononen et al., 2016)					Volumes of harvested production (ton year^{-1})	(Maes et al., 2015)
										Surface area of crops (ha)	(Maes et al., 2015)
Biomass: raw materials	√	√			(Asmus et al., 2019; Chung et al., 2015; Depellegrin et al., 2020; Mononen et al., 2016; Willaert et al., 2019)				Animals reared for nutritional purposes	Seafood: Fishing intensity expressed in hours for the year	(Depellegrin et al., 2020)
										The amounts of aquaculture production (in metric tons)	(Chung et al., 2015)
										Animal products (kg)	(Mononen et al., 2016)
Energy	√		√	√	(Depellegrin et al., 2020; Mononen et al., 2016)				Cultivated terrestrial plants for nutrition, materials or energy	Offshore Wind Energy: Potential offshore wind energy development sites (km^2)	(Depellegrin et al., 2020)
										Total timber removal (m^3 year^{-1}); Timber growing stock (m^3)	(Maes et al., 2015)
										Harvest energy content; Harvested production of energy crops (ton year^{-1})	(Mononen et al., 2016); (Maes et al., 2015)
Water for drinking	√	√	√	√	(Mansur et al., 2016; Mononen et al., 2016)	√		(Mansur et al., 2016)	Water used for nutrition, materials or energy	Proportion of renewable water withdrawn for public use (%)	(Maes et al., 2015)
										Use of raw water (m^3)	(Mononen et al., 2016)
										Total water abstraction for public use (m^3)	(Maes et al., 2015)

Water for non-drinking purposes	√	√			(Chung et al., 2015)					Total water abstraction for industrial use (m^3)	(Maes et al., 2015)
										Proportion of renewable water withdrawn for industrial use (%)	(Maes et al., 2015)
										Total water abstraction for agricultural use (m^3)	(Maes et al., 2015)
										Proportion of renewable water withdrawn for agricultural use (%)	(Maes et al., 2015)
Regulation & Maintenance											
Water regulation	√	√	√	√	(Asmus et al., 2019; Chung et al., 2015; Lilai et al., 2016; Mansur et al., 2016; Mononen et al., 2016; Willaert et al., 2019)	√	√	(Lilai et al., 2016; Mansur et al., 2016)	Regulation of the chemical condition of water by living processes	Water purification	(Chung et al., 2015; Mansur et al., 2016)
										Groundwater production (recharge rate, mm ha^{-1}year^{-1})	(Mononen et al., 2016)
										Water Retention Index [dimensionless between 0-10]	(Maes et al., 2015)
Erosion regulation	√	√	√	√	(Depellegrin et al., 2020; Mononen et al., 2016; Willaert et al., 2019)				Control of erosion rates	Capacity of ecosystems to avoid soil erosion [dimensionless between 0-1]	(Maes et al., 2015)
										Demand for erosion control from coastal population [index]	(Depellegrin et al., 2020)
										Soil retention (ton ha^{-1} year^{-1})	(Maes et al., 2015)
Habitat	√		√	√	(Asmus et al.,	√	√	(Mansur et	Maintaining nursery	Surface area of forest	(Maes et al., 2015)

protection					2019; Mansur et al., 2016)			al., 2016; Silver et al., 2019)	populations and habitats (Including gene pool protection)	with a protective function (ha)	
										Crop production deficit (%)	(Maes et al., 2015)
Biodiversity	√	√			(Depellegrin et al., 2020)					Species richness	(Maes et al., 2015)
										Habitat quality based on common birds [dimensionless ratio]	(Maes et al., 2015)
										Interpolated biodiversity status [index]	(Depellegrin et al., 2020)
Pollination			√	√	(Mononen et al., 2016)				Seed dispersal	Increase in yield (kg ha^{-1})	(Mononen et al., 2016)
										Pollination potential [dimensionless between 0-1]	(Maes et al., 2015)
Air quality regulation	√	√	√	√	(Chung et al., 2015; Mononen et al., 2016; Willaert et al., 2019)				Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	Proportion of green areas in the high density area of cities (%)	(Maes et al., 2015)
										Removal of NO_2 by urban vegetation (ton ha^{-1} year^{-1})	(Maes et al., 2015)
										PM_{10} annual mean concentration (µg m^{-3})	(Baró et al., 2015)
										NO_2 annual mean concentration (µg m^{-3})	(Baró et al., 2015)
										The highest O_3 value based on daily max 8-h averages (µg m^{-3})	(Baró et al., 2015)
Soil quality regulation	√	√	√	√	(Mononen et al., 2016)				Weathering processes and their effect on soil quality; Decomposition and	Increased harvest (ha)	(Mononen et al., 2016)
										Nitrogen fixation rate	(Mononen et al., 2016)
										Gross nitrogen balance (ton year^{-1})	(Maes et al., 2015)

									fixing processes and their effect on soil quality	Aggregated index of nutrient recycling potential as function of substrate type [index]	(Depellegrin et al., 2020)
										Improved water and soil quality [qualitative scale]	(Mononen et al., 2016)
Climate regulation	√	√	√	√	(Chung et al., 2015; Lilai et al., 2016; Mansur et al., 2016; Mononen et al., 2016)	√	√	(Lilai et al., 2016; Mansur et al., 2016)	Regulation of temperature and humidity, including ventilation and transpiration	Carbon storage	(Chung et al., 2015)
										Net ecosystem productivity [normalised index between 0-1]	(Maes et al., 2015)
										Forest carbon potential (percent change, %)	(Maes et al., 2015)
										Annual CO_2-eq emissions per ha ($t^{-1}capita^{-1}year^{-1}$); Annual CO_2-eq emissions per capita ($t^{-1}capita^{-1}year^{-1}$)	(Baró et al., 2015)
										Carbon-storing habitats (ha)	(Mononen et al., 2016)
										Overall coverage of forest (%)	(Tuvendal and Elmqvist, 2011)
Natural hazard protection			√	√	(Mansur et al., 2016; Mononen et al., 2016)	√		(Mansur et al., 2016)	Wind protection	Undrained habitats, vegetation type and cover (ha)	(Mononen et al., 2016)
										Percentage of windbreaks (%)	(Haines-Young and Potschin, 2018)
Cultural											
Recreation	√	√	√	√	(Depellegrin et al., 2020; Mononen et al.,				Characteristics of living systems that enable scientific	Aggregated index generated through recreation and tourism	(Depellegrin et al., 2020)

					2016)				investigation or the creation of traditional ecological knowledge	statistics [index]	
										Experience: participation in recreational activities (n,%) or outdoor activities (n)	(Mononen et al., 2016)
										Share of high provision easily accessible land in the recreation opportunity spectrum (%)	(Maes et al., 2015)
										Surface area of special protection area (ha)	(Maes et al., 2015)
										Surface area of sites of community importance (ha)	(Maes et al., 2015)
Aesthetic	√	√	√	√	(Chung et al., 2015; Depellegrin et al., 2020; Mansur et al., 2016; Willaert et al., 2019)	√	√	(Lilai et al., 2016; Mansur et al., 2016)	Characteristics of living systems that enable aesthetic experiences	Employment (n); Tourism revenue	(Mononen et al., 2016)
										Cumulative viewshed from bathing areas using viewshed analysis techniques representing the sum of observations with observer height 1.7 m [no. of obervations]	(Depellegrin et al., 2020)
Natural and cultural Heritage	√	√	√	√	(Depellegrin et al., 2020; Mononen et al., 2016; Willaert et al., 2019)				Characteristics of living systems that are resonant in terms of culture or heritage	Intensity of natural and cultural heritage protection based on the number of protected areas overlapping (km^2)	(Depellegrin et al., 2020)

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Appendix 2 Overview of main interlinkages between three main vulnerability domains (Chapter 2)

Appendix 2 provides an overview of the main interlinkages between ecosystem vulnerability, ecosystem services and social vulnerability. It also contains narrative descriptions and supporting evidence for the identification of corresponding ecosystem service indicators. Furthermore, it presents a set of possible ecosystem service indicators that could be used in case studies.

The example indicators, under both ecosystem and social vulnerability contexts, are from the reviewed articles on vulnerability and risk assessment. If there are no indicators under that column, it means there are no indicators available in the previous research.

Provisioning

Ecosystem type	**Ecosystem service**
Agroecosystem	Biomass (food)

Relevant aspects

Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Habitat degradation: soil quality	Cropping system: condition of croplands	Provisioning: Biomass (food)	Agriculture: agricultural income	Human livelihoods

Relevancy (based on literature)

Cropping system: condition of croplands → Provisioning: Biomass (food) → Agriculture → Human livelihoods

In terms of ecosystem vulnerability, the condition of croplands represents agroecosystem, farmland and habitats with considerable coverage of the natural environment. It directly affects the provisioning services (agricultural production) of the agroecosystems. The cropping system is susceptible both in terms of ecosystem conditions and economic aspects when exposed to natural hazards. Especially in rural areas, most family's income and livelihoods are very dependent on agricultural income. For provisioning services, agricultural productivity is mainly considered, through e.g. the indicator 'per capita volumes of harvested production'.

Some factors related to the biophysical environment, such as soil quality, are related to the provisioning services. They will be considered in the section concerning regulation & maintenance services below.

Key literature

(Maes et al., 2015)

Possible ecosystem indicator

Volumes of harvested production (ton year^{-1} per capita)	(Maes et al., 2015)

Provisioning				
Ecosystem type Agroecosystem			**Ecosystem service** Timber (energy/processing use)	
Relevant aspects				
Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Habitat degradation: soil quality	Habitat: managed forests	Provisioning: Energy	Forest: wood trade	Human livelihoods
Relevancy (based on literature)				
Managed forests → Provisioning: Energy → Forest: wood trade → Human livelihoods Materials from plants can be used for energy supply (harvested production of energy crops) or non-nutritional purposes (processing use). Similar to biomass, energy crops are used as raw materials and are directly related to human livelihoods. Energy crops or wood productivity is mainly regarded as provisioning services, through e.g. indicator 'per capita harvested production of energy crops'.				
Key literature (Haines-Young and Potschin, 2018a)				
Possible ecosystem indicator				
Harvested production of energy crops (ton year^{-1} per capita)			(Maes et al., 2015)	

Provisioning

Ecosystem type	**Ecosystem service**
Aquatic ecosystem	Water

Relevant aspects

Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Habitat destruction Indicator: freshwater scarcity (average freshwater availability)	Water sources	Provisioning: Water	Agriculture, industry and public use	Human livelihoods

Relevancy (based on literature)

Water sources → Provisioning: Water → Agriculture, industry and public use → Human livelihoods

The land underground surfaces hold natural water sources. Water resources are linked to provisioning, regulating and cultural services. Water issues such as freshwater scarcity could lead to significant negative impacts both for habitats and social systems. Humans consume water supplied by the public water supply system based on government sector and profit company management. The capacity to obtain safe drinking water is directly related to human livelihoods and health. Meanwhile, the role of water in agriculture, industry and municipalities is critical. For water provisioning service, indicators 'total water abstraction for public use (m^3 per capita)' and 'total water abstraction for agriculture and industry use (m^3 per capita)' are selected to show the dependency of the social system on water.

Some factors related to the biophysical environment, such as water quality, are related to the water provision. It will be considered in the subsequent section of regulation & maintenance services.

Key literature

(Aylward et al., 2005)

Possible ecosystem indicator

Total water abstraction for public use (m^3 per capita)	(Maes et al., 2015)
Total water abstraction for agriculture and industry use (m^3 per capita)	(Maes et al., 2015)
Groundwater production ($mm\ ha^{-1} year^{-1}$)	(Mononen et al., 2016)

<table>
<tr><td colspan="5">**Provisioning**</td></tr>
<tr><td colspan="3">**Ecosystem type**
Aquaculture ecosystem</td><td colspan="2">**Ecosystem service**
Biomass (aquaculture)</td></tr>
<tr><td colspan="5">**Relevant aspects**</td></tr>
<tr><td>**Ecosystem vulnerability context:** Ecosystem susceptibility</td><td>**Ecological process/function in ecosystem & habitat**</td><td>**Ecosystem service**</td><td>**Societal benefit/human well-being**</td><td>**Social vulnerability context:** Social susceptibility</td></tr>
<tr><td>Habitat degradation: water quality</td><td>Habitat: condition of freshwater ecosystems</td><td>Provisioning: Biomass (aquaculture)</td><td>Fisheries</td><td>Human livelihoods</td></tr>
<tr><td colspan="5">**Relevancy (based on literature)**</td></tr>
<tr><td colspan="5">*Condition of freshwater ecosystems → Provisioning: Biomass (aquaculture) → Fisheries → Human livelihoods*

In terms of ecosystem vulnerability, the condition of freshwater ecosystems directly affects the provisioning services (aquacultural production) of the aquaculture ecosystems. Similar to agroecosystems, aquaculture products are used as raw materials for food production and are directly related to human livelihoods. In this research, aquacultural productivity is mainly considered through the indicator per capita amounts of aquaculture production'.

Besides, the productivity of aquaculture products is also related to freshwater quality, which has been considered in regulation & maintenance services.</td></tr>
<tr><td colspan="5">**Key literature**
(Haines-Young and Potschin, 2018b; Harrison et al., 2014)</td></tr>
<tr><td colspan="5">**Possible ecosystem indicator**</td></tr>
<tr><td colspan="3">The amounts of aquaculture production (kg per capita)</td><td colspan="2">(Chung et al., 2015)</td></tr>
</table>

Regulation & Maintenance

Ecosystem type	**Ecosystem service**
Terrestrial ecosystem	Soil quality regulation

Relevant aspects

Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Habitat degradation: soil quality Indicator: Cation exchange capacity; Soil organic matter	Habitat condition: nutrient cycling	Regulation & Maintenance: Soil quality regulation	Human livelihoods: agriculture and forest products	Human livelihoods

Relevancy (based on literature)

Nutrient cycling → Soil quality regulation → Agricultural productivity → Human livelihoods

Current vulnerability research considers habitat degradation, which includes indicators that take into account soil organic matter and cation exchange capacity. However, soil organic matter content mainly shows the capacity of soils to provide organic matter and does not represent the amount of nutrients that plants can access. When nutrients that were originally in the organic form are absorbed by plants through mineralization, this represents the final ecosystem services through nutrient cycling. Considering nitrogen fixation rate or gross nitrogen balance could take into account ecological functions with their actual utility extent.

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. The ecological process based on soil quality regulation service is nutrient cycling, which includes the recovery and reuse of nutrients in soil organic residues. For example, aggregated index of nutrient recycling potential could demonstrate the potential for nutrient cycling by soils. Overall, soil quality regulation services indirectly act on the social system through provisioning services such as agricultural production and then affect social benefits and human activities.

Key literature

(Hagenlocher et al., 2018; Haines-Young and Potschin, 2018b; Schröder et al., 2016)

Possible ecosystem indicator

Aggregated index of nutrient recycling potential [index]	Depellegrin et al. (2020)
Nitrogen fixation rate (%)	(Mononen et al., 2016)
Gross nitrogen balance (ton year^{-1})	(Maes et al., 2015)

Regulation & Maintenance	
Ecosystem type Terrestrial ecosystem	**Ecosystem service** Erosion regulation

Relevant aspects

Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Habitat degradation: Soil quality Indicator: Thickness of the soil organic layer	Habitat condition: Sediment stabilisation	Regulation & Maintenance: Erosion regulation	Human livelihoods: Increased production/agricultural income	Human livelihoods

Relevancy (based on literature)

Sediment stabilisation → Erosion regulation → Agricultural productivity → Human livelihoods

The occurrence of erosion would affect soil quality and further affect the net productivity of agroecosystems. Current vulnerability research involves habitat degradation aspect, which includes indicators like the thickness of the soil organic layer that influences runoff and soil erosion. The thickness of the soil organic layer can show the ability of soil to provide organic matter to a certain extent, but it is difficult to represent the specific impact on erosion and soil retention. Data availability for this indicator is also very sparse.

From the perspective of erosion regulation service, plants and animals play a role in preventing or reducing the occurrence of soil loss through sediment stabilisation. Ecosystem services like "average transported sediment at the outlet" could reveal the capacity of the ecosystem to regulate soil erosion. Similar to soil quality regulation services, erosion regulation services affect provisioning services such as agricultural productivity by mitigating or preventing potential degradation of soils, thereby affecting social benefits and human activities.

Erosion regulation indicators can be used as vulnerability indicators to measure the ability to sediment stabilisation of ecosystems.

Key literature

(Frank et al., 2014; Haines-Young and Potschin, 2018b)

Possible ecosystem indicator	
Average transported sediment at the outlet (ton year^{-1})	(Zhang et al., 2019)
Capacity of ecosystems to avoid soil erosion [dimensionless between 0-1]	(Maes et al., 2015)
Soil retention (ton ha^{-1} year^{-1})	(Maes et al., 2015)

Regulation & Maintenance				
Ecosystem type Agroecosystem			**Ecosystem service** Pollination	
Relevant aspects				
Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Ecosystem: biodiversity	Cropping system: insects and seed dispersal	Regulation & Maintenance: Pollination	Agricultural productivity: Increased production/agricultural income	Human livelihoods
Relevancy (based on literature)				
Ecosystem: biodiversity → Cropping system: insects and seed dispersal → Pollination → Agricultural productivity → Human livelihoods An agroecosystem is highly dependent on pollination services. The presence of pollinating insects or seed dispersal benefits the productivity of many crops. Meanwhile, pollination service is highly related to biodiversity. Like other regulation and maintenance services, pollination service affects human livelihoods by affecting the productivity of crops. The indicator 'Pollination potential' could be a supplementary indicator to show the impact of the ecosystem on agriculture.				
Key literature (Aizen et al., 2009)				
Possible ecosystem indicator				
Pollination potential [dimensionless between 0-1]			(Maes et al., 2015)	

Regulation & Maintenance

Ecosystem type	**Ecosystem service**
Terrestrial ecosystem	Natural hazard protection

Relevant aspects

Ecosystem vulnerability context	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Ecosystem robustness	Wind breaks	Regulation & Maintenance: Natural hazard protection	Wind protection	Human health & security

Relevancy (based on literature)

Wind breaks → Regulation & Maintenance: Natural hazard protection → Wind protection → Human health & security

The presence of plants could mitigate the wind speed and then reduce the damage to croplands and living system. For example, the windbreaks can protect crops, people and buildings from winds. Natural hazard protection could be measured through the proportion of windbreaks with dense woods and plants.

Indicator 'Percentage of windbreaks (%)' is regarded as an indicator to represent the natural hazard protection. Besides, indicator 'undrained habitats, vegetation type and cover' is also added to fully present the ability to reduce wind-related hazards.

Key literature

Haines-Young and Potschin (2018)

Possible ecosystem indicator

Undrained habitats, vegetation type and cover (ha per capita)	(Mononen et al., 2016)
Percentage of windbreaks (%)	(Haines-Young and Potschin, 2018b)

Regulation & Maintenance

Ecosystem type	Ecosystem service
Terrestrial ecosystem	Air quality regulation

Relevant aspects

Ecosystem vulnerability context: Ecosystem robustness	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Ecosystem robustness	Atmospheric condition	Regulation & Maintenance: Air quality regulation	Mitigating harmful effect of living system	Human health

Relevancy (based on literature)

Air quality → Atmospheric condition → Regulation & Maintenance: Air quality regulation → Mitigating harmful effect of living system → Human health

Atmospheric condition and air quality are critical to the condition of living system and human health. Urban trees and plants mediate toxic substances of anthropogenic origin through living processes. For example, shelterbelts play a role in dust filtration in air quality regulation, which mitigates the harmful effect of living system. Besides, a series of air quality indicators are also included to demonstrate the air quality regulation services of the ecosystem.

Key literature

Haines-Young and Potschin (2018)

Possible ecosystem indicator

Removal of NO_2 by urban vegetation (ton ha^{-1} $year^{-1}$)	(Baró et al., 2015)
PM_{10} annual mean concentration ($\mu g\ m^{-3}$); NO_2 annual mean concentration ($\mu g\ m^{-3}$); O_3 value based on daily max 8-h averages ($\mu g\ m^{-3}$)	(Baró et al., 2015)

<table>
<tr><th colspan="5">Regulation & Maintenance</th></tr>
<tr><td colspan="3">Ecosystem type
Terrestrial ecosystem</td><td colspan="2">Ecosystem service
Climate regulation</td></tr>
<tr><td colspan="5">Relevant aspects</td></tr>
<tr><td>Ecosystem vulnerability context</td><td>Ecological process/function in ecosystem & habitat</td><td>Ecosystem service</td><td>Societal benefit/human well-being</td><td>Social vulnerability context: Social susceptibility</td></tr>
<tr><td>Ecosystem robustness</td><td>Atmospheric condition</td><td>Regulation & Maintenance: Climate regulation</td><td>Mitigating harmful effect of living system</td><td>Human health</td></tr>
<tr><td colspan="5">Relevancy (based on literature)</td></tr>
<tr><td colspan="5"><i>Air quality → Atmospheric condition → Regulation & Maintenance: Climate regulation → Mitigating harmful effect of living system → Human health</i>
Climate regulation can regulate can chemical composition of atmosphere and oceans, such as the regulation of the concentrations of gases in the atmosphere. The mitigation benefits can represent climate regulation services, including carbon storage and sequestration currently being considered in forest policy management. Two climate regulation indicators are added in this research, namely 'Carbon-storing habitats' and 'forest carbon potential'.</td></tr>
<tr><td colspan="5">Key literature
Haines-Young and Potschin (2018); (Keith et al., 2021)</td></tr>
<tr><td colspan="5">Possible ecosystem indicator</td></tr>
<tr><td colspan="3">Carbon-storing habitats (ha per capita)</td><td colspan="2">(Mononen et al., 2016)</td></tr>
<tr><td colspan="3">Forest carbon potential (percent change, %)</td><td colspan="2">(Maes et al., 2015)</td></tr>
</table>

<table>
<tr><th colspan="10">Regulation & Maintenance</th></tr>
<tr><td colspan="5">Ecosystem type
Aquatic ecosystem</td><td colspan="5">Ecosystem service
Water regulation</td></tr>
<tr><td colspan="10">Relevant aspects</td></tr>
<tr><td colspan="2">Ecosystem vulnerability context: Ecosystem susceptibility</td><td colspan="2">Ecological process/function in ecosystem & habitat</td><td colspan="2">Ecosystem service</td><td colspan="2">Societal benefit/human well-being</td><td colspan="2">Social vulnerability context: Social susceptibility</td></tr>
<tr><td colspan="2">Habitat degradation

Indicator: water quality; groundwater quality</td><td colspan="2">Water purification;
Water Retention</td><td colspan="2">Regulation & Maintenance: Water regulation</td><td colspan="2">Agriculture, industry and public use</td><td colspan="2">Human livelihoods</td></tr>
<tr><td colspan="10">Relevancy (based on literature)</td></tr>
<tr><td colspan="10"><i>Water purification & Water Retention → Regulation & Maintenance: Water regulation → Agriculture, industry and public use → Human livelihoods</i>

The control and maintenance of water bodies by plants or animals provide a normal chemical condition. For example, the excess nitrogen in water can be filtered by rivers and streams, lakes, estuaries and coastal marshes. The removal of polluted nitrogen results in improved water quality in downstream areas. This service enables humans to make better use of water and reduces water purification costs.

Current vulnerability research involves habitat degradation aspect, which includes indicators that take into account water quality and groundwater quality. From the perspective of water regulation service, both water quality and groundwater quality are related to water purification service. The actual application usually requires the use of feasible proxy indicators. For example, the proxy indicator “upstream protected land (ha)” can be used to represent where water quality is expected to be better. Besides, this research adds the indicator 'water retention index' which takes into account potential water retention in vegetation, water bodies as well as soil and underlying aquifers.</td></tr>
<tr><td colspan="10">Key literature
(Maes et al., 2012)</td></tr>
<tr><td colspan="10">Possible ecosystem indicator</td></tr>
<tr><td colspan="6">Water Retention Index [index]</td><td colspan="4">(Vandecasteele et al., 2018)</td></tr>
<tr><td colspan="6">Water quality [index]</td><td colspan="4">Hagenlocher et al. (2018)</td></tr>
<tr><td colspan="6">Groundwater quality [index]</td><td colspan="4">Hagenlocher et al. (2018)</td></tr>
</table>

<table>
<tr><td colspan="5">Cultural</td></tr>
<tr><td colspan="2">Ecosystem type
Terrestrial ecosystem</td><td colspan="3">Ecosystem service
Recreation</td></tr>
<tr><td colspan="5">Relevant aspects</td></tr>
<tr><td>Ecosystem vulnerability context: Ecosystem susceptibility</td><td>Ecological process/function in ecosystem & habitat</td><td>Ecosystem service</td><td>Societal benefit/human well-being</td><td>Social vulnerability context: Social susceptibility</td></tr>
<tr><td>Ecosystem: biodiversity</td><td>Ecosystem condition</td><td>Cultural: Recreation</td><td>Human perception</td><td>Human health
Indicator: Percentage of tourism to GDP (%)</td></tr>
<tr><td colspan="5">Relevancy (based on literature)</td></tr>
<tr><td colspan="5"><i>Ecosystem: Biodiversity → Ecosystem condition → Cultural: Recreation → Human perception → Human health</i>
Humans use the natural environment for sports and entertainment. This kind of cultural services is closely related to the biophysical characteristics and quality of natural environment, such as species diversity. Humans enjoy the services provided by nature in particular to relieve stress. It could mitigate harmful effect of living system and improve the perceived service quality of human.
Based on the literature, indicator 'aggregated index generated through recreation and tourism statistics [index]' or 'percentage of tourism to GDP (%)' could be used to laterally measure the recreation service provided by ecosystem.</td></tr>
<tr><td colspan="5">Key literature
Haines-Young and Potschin (2018)</td></tr>
<tr><td colspan="5">Possible ecosystem indicator</td></tr>
<tr><td colspan="3">Aggregated index generated through recreation and tourism statistics [index]</td><td colspan="2">(Depellegrin et al., 2020)</td></tr>
<tr><td colspan="3">Percentage of tourism to GDP (%)</td><td colspan="2">(Depellegrin et al., 2020)</td></tr>
</table>

Cultural	
Ecosystem type Terrestrial ecosystem	**Ecosystem service** Aesthetic; Natural and cultural heritage

Relevant aspects

Ecosystem vulnerability context: Ecosystem susceptibility	**Ecological process/function in ecosystem & habitat**	**Ecosystem service**	**Societal benefit/human well-being**	**Social vulnerability context:** Social susceptibility
Ecosystem: biodiversity	Ecosystem condition	Cultural: Aesthetic	Human perception	Human health Indicator: Percentage of tourism to GDP (%)

Relevancy (based on literature)

Ecosystem: Biodiversity → Ecosystem condition → Cultural: Aesthetic → Human perception → Human health

High-quality environment (scenic area) and natural and cultural heritage provide beauty and inspiration for human. Human enjoys the beauty of the natural environment, which is beneficial for human mental health. This kind of cultural service is closely related to biophysical characteristics, such as biodiversity.

In addition to the species richness indicator, indicator 'habitat quality based on common birds [dimensionless ratio]' could be a proxy indicator of the ability of ecosystem for providing aesthetic value for human perception. Indicator 'intensity of natural and cultural heritage protection based on the number of protected areas overlapping' could be an indicator to measure the impact of natural and cultural heritage on human society. Indicator 'employment in tourism and other aesthetic activities (%)' could also be an indicator to measure the impact of cultural services on human society.

Key literature

Haines-Young and Potschin (2018)

Possible ecosystem indicator	
Employment in tourism and other aesthetic activities (%)	(Mononen et al., 2016)
Habitat quality based on common birds [dimensionless ratio]	(Maes et al., 2015)
Intensity of natural and cultural heritage protection based on the number of protected areas overlapping (km^2)	(Depellegrin et al., 2020)

<table>
<tr><td colspan="5">Cultural</td></tr>
<tr><td colspan="2">Ecosystem type
Terrestrial ecosystem</td><td colspan="3">Ecosystem service
Biodiversity</td></tr>
<tr><td colspan="5">Relevant aspects</td></tr>
<tr><td>Ecosystem vulnerability context: Ecosystem susceptibility</td><td>Ecological process/function in ecosystem & habitat</td><td>Ecosystem service</td><td>Societal benefit/human well-being</td><td>Social vulnerability context: Social susceptibility</td></tr>
<tr><td>Ecosystem: biodiversity
Indicator: Species richness adjusted by intactness</td><td>Ecosystem: species richness</td><td>Regulation & Maintenance: Biodiversity</td><td>Human perception</td><td>Percentage of tourism to GDP (%)</td></tr>
<tr><td colspan="5">Relevancy (based on literature)</td></tr>
<tr><td colspan="5"><i>Ecosystem: Species richness → Regulation & Maintenance: Biodiversity → Human perception → Tourism and other cultural activities</i>
There are positive correlations between biodiversity, ecological functions and other provisioning services, and these relationships directly depend on the conditions of ecosystems and habitats. Biodiversity is closely related to human well-being and livelihood.
Previous ecosystem susceptibility component has considered biodiversity indicator (such as species richness). In this research, it is classified into the cultural classification, whether in cultural perception or economic activities such as tourism.</td></tr>
<tr><td colspan="5">Key literature
(Liquete et al., 2016) and references therein</td></tr>
<tr><td colspan="5">Possible ecosystem indicator</td></tr>
<tr><td colspan="3">Species richness [index]</td><td colspan="2">Hagenlocher et al. (2018)</td></tr>
</table>

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Appendix 3 List of vulnerability and risk assessment indicators (Chapter 2)

Appendix 3 provides an overview of potential indicators of vulnerability and risk assessments in deltas. Indicators are grouped according to the Delta-ES-SES framework.

Risk components	Indicator	References
Hazard		
Hazard severity (Flooding, cyclones, storm surge and drought)	Average of monthly precipitation	(Prabnakorn et al., 2019)
	Significant wave height	(Li et al., 2015)
	Shoreline change rates	(Li et al., 2015)
	Tidal range	(Li et al., 2015)
	Sea level rise	(Li et al., 2015)
	Water level/cm	(Xianwu et al., 2020)
Salinity intrusion severity	Concentration of salts (5g/l or more)	Hagenlocher et al (2018)
Hazard duration	Hazard duration/days	(Shah et al., 2020)
Hazard frequency	Probability of occurrence	(Shah et al., 2020)
Exposure		
Exposed ecosystem	Ecosystem exposed to flooding (%)	Hagenlocher et al (2018)
	Ecosystem exposed to cyclones (%)	Hagenlocher et al (2018)
	Ecosystem exposed to storm surge (%)	Hagenlocher et al (2018)
	Ecosystem exposed to drought (%)	Hagenlocher et al (2018)
	Ecosystem exposed to salinity intrusion (%)	Hagenlocher et al (2018)
Exposed population	Percentage of population exposed to flooding (%)	Hagenlocher et al (2018)
	Percentage of population exposed to cyclones (%)	Hagenlocher et al (2018)
	Percentage of population exposed to cyclones (%)	Hagenlocher et al (2018)

	Percentage of population exposed to drought (%)	Hagenlocher et al (2018)
	Percentage of population exposed to salinity intrusion (%)	Hagenlocher et al (2018)
Exposed economy	Proportion of GDP in primary sector (%)	(Ge et al., 2017)
Exposed infrastructure	Proportion of critical transportation sector: main road, main tunnel, subway, port, airport; Water sector; energy sector; Information and communication sector; civil administration buildings sector (%)	(Sun et al., 2019)
Ecosystem service		
Provisioning	Volumes of harvested production (ton year^{-1} per capita)	Maes et al (2015)
	Harvested production of energy crops (ton year^{-1} per capita)	Maes et al (2015)
	Total water abstraction for public use (m^{3} per capita)	Maes et al (2015)
	Total water abstraction for agriculture and industry use (m^{3} per capita)	Maes et al (2015)
	Groundwater production (recharge rate, mm ha^{-1}year^{-1})	(Mononen et al., 2016)
	Rates of surface water drainage (m^{3}/s)	(Shah et al., 2020)
	Aquaculture production (kg per capita)	Chung et al (2015)
Regulation & Maintenance	Aggregated index of nutrient recycling potential [index]	Depellegrin et al (2020)
	Nitrogen fixation rate (%)	(Mononen et al., 2016)
	Gross nitrogen balance (ton year^{-1})	Maes et al (2015)
	Average transported sediment at the outlet (ton year^{-1})	Zhang et al (2019)
	Capacity of ecosystems to avoid soil erosion [dimensionless between 0-1]	Maes et al (2015)
	Soil retention (ton ha^{-1}year^{-1})	Maes et al (2015)
	Potential increase in agricultural production to compensate the reduction due to the climate change (%)	(Sebesvari et al., 2016)
	Pollination potential [dimensionless between 0-1]	Maes et al (2015)
	Species richness [index]	Hagenlocher et al (2018)
	Percentage of windbreaks (%)	(Haines-Young and Potschin, 2018)
	Undrained habitats, vegetation type and cover (ha per capita)	(Mononen et al., 2016)
	Carbon-storing habitats (ha per capita)	(Mononen et al., 2016)
	Forest carbon potential (percent change, %)	Maes et al (2015)
	Removal of NO_2 by urban vegetation (ton ha^{-1} year^{-1})	Maes et al (2015)

	PM_{10} annual mean concentration ($\mu g\ m^{-3}$); NO_2 annual mean concentration ($\mu g\ m^{-3}$); O_3 value based on daily max 8-h averages ($\mu g\ m^{-3}$)	Baró et al (2015)
	Water quality [index]	Hagenlocher et al (2018)
	Groundwater quality [index]	Hagenlocher et al (2018)
	Water Retention Index [index]	Vandecasteele et al (2018)
Cultural	Aggregated index generated through recreation and tourism statistics [index]	Depellegrin et al (2020)
	Percentage of tourism to GDP (%)	Depellegrin et al (2020)
	Intensity of natural and cultural heritage protection based on the number of protected areas overlapping (km^2)	Depellegrin et al (2020)
	Employment in tourism and other aesthetic activities (%)	(Mononen et al., 2016)
	Habitat quality based on common birds [dimensionless ratio]	Maes et al (2015)
Ecosystem susceptibility		
Habitat destruction	Percentage of vegetation loss (%)	(Sebesvari et al., 2016)
	Percentage of mangrove area loss (%)	(Sebesvari et al., 2016)
	Percentage of wetland loss (%)	Hagenlocher et al (2018)
	Percentage of deforested area (%)	Hagenlocher et al (2018)
	Percentage of area covered by "problem soils" (%)	Hagenlocher et al (2018)
	Percentage of shoreline eroded (%)	Hagenlocher et al (2018)
Habitat degradation	Increased use of chemicals and fertilisers (qualitative/ quantitative)	(Shah et al., 2020)
	Water clarity (Turbidity, Secchi depth)	(Shah et al., 2020)
	Normalized Difference Vegetation Index (NDVI)	(Shah et al., 2020)
	Land reclamation rate (km^2/year)	(Shah et al., 2020)
	Degree of pollution in sediments (heavy metals, etc.) (proxy - concentration of heavy metals in sediments)	(Shah et al., 2020)
	Proportion of area covered by algal boom (%)	(Shah et al., 2020)
Habitat fragmentation	Forest connectivity [index]	Hagenlocher et al (2018)
	Wetland connectivity [index]	Hagenlocher et al (2018)
	River connectivity [index]	Hagenlocher et al (2018)

	River net density (defined as river length divided by land area) [index]	(Yang et al., 2014)
Ecosystem robustness		
Ecosystem & Habitat	Ecosystem Functionality Index (EFI)	Hagenlocher et al (2018)
	Mean Species Abundance (MSA)	Hagenlocher et al (2018)
	Percentage of change in land use (agriculture, vegetation, fishery, settlement) (%)	(Sebesvari et al., 2016)
	Number of aquatic environmental reservoirs (n)	(Sebesvari et al., 2016)
Ecosystem conservation	Percentage of area covered by Wetlands of International Importance (Ramsar Sites) (%)	Hagenlocher et al (2018)
	Percentage of government expenditure on environmental protection (%)	Hagenlocher et al (2018)
	Policies supporting biodiversity conservation (yes/no)	Hagenlocher et al (2018)
	Policies for coastal protection (yes/no)	Hagenlocher et al (2018)
	Participation in treaties, such as Convention on Biological Diversity (yes/no)	Hagenlocher et al (2018)
	Government expenditure on environmental protection (% expenditure)	Hagenlocher et al (2018)
Ecosystem restoration	Percentage of nature reserves and wetlands (%)	(Li et al., 2015)
	Percentage of mangrove area restored (%)	Hagenlocher et al (2018)
	Percentage of forest area restored (%)	Hagenlocher et al (2018)
	Rate of afforestation area (ha)	(Shah et al., 2020)
Agriculture	Proportion of drought tolerant crops (% of crop production)	(Shah et al., 2020)
	Percent of area with Intensive/ extensive agriculture in floodplain (% of agriculture land)	(Shah et al., 2020)
Social susceptibility		
Key services	Percentage of households without access to irrigation (%)	Hagenlocher et al (2018)
	Percentage of population without access to (improved) sanitation (%)	Hagenlocher et al (2018)
	Percentage of population without access to clean water (%)	Hagenlocher et al (2018)
	Percentage of population without access to electricity (%)	Hagenlocher et al (2018)
	Percentage of population living in informal settlements (%)	Hagenlocher et al (2018)
	Proportion of houses with poor facilities that are more fragile to climate change and hazards (%)	(Ge et al., 2017)
	Percentage of households that live in rented houses (%)	(Yang et al., 2019)

	The household proportion with person aged 65 and older (%)	(Yang et al., 2019)
	Percentage of reinforced/elevated houses (%)	Hagenlocher et al (2018)
	Percentage of floating houses (%)	Hagenlocher et al (2018)
	Percentage of houses with more than one floor (%)	Hagenlocher et al (2018)
	Percentage of households without official land title (%)	Hagenlocher et al (2018)
Human livelihoods	Population density (Population per km^2)	(Yang et al., 2014)
	Percentage female-headed households (%)	Hagenlocher et al (2018)
	Travel time to closest city (mins)	Hagenlocher et al (2018)
	Percentage of the population with disabilities (%)	Hagenlocher et al (2018)
	Percentage malnourished population (%)	Hagenlocher et al (2018)
	Percentage of population with chronic illnesses (%)	Hagenlocher et al (2018)
	Percentage of illiterate population (%)	Hagenlocher et al (2018)
	Proportion of families below poverty line in total households	(Zhang et al., 2020)
	Dependency ratio (%)	Hagenlocher et al (2018)
	GINI index (0-100)	Hagenlocher et al (2018)
	Dependency on agriculture / forestry / fisheries for livelihood (%)	Hagenlocher et al (2018)
	Percentage of primary industry to GDP (%)	(Yang et al., 2019)
Human health & security	Ratio of afforestation coverage areas in the city	(Yang et al., 2014)
	Prevalence of population who experience violence (%)	Hagenlocher et al (2018)
	Prevalence of population affected by armed conflict (%)	Hagenlocher et al (2018)
	Number of fatalities caused by terrorists per 10,000 per year	Hagenlocher et al (2018)
Coping capacity		
Individual and household	Per capita GDP per unit area	(Zhang et al., 2017)
	Per capita income	(Yang et al., 2019)
	Average years of education (year)	Hagenlocher et al (2018)
	Ratio of the population with college/university degree or higher (%)	Hagenlocher et al (2018)
	Percentage of households without individual means of transportation (%)	Hagenlocher et al (2018)
	Percentage of households without gross savings (%)	Hagenlocher et al (2018)
	Percentage of households without access to bank loans / (micro-) credits (%)	Hagenlocher et al (2018)

	Lending interest rate (%)	Hagenlocher et al (2018)
	Percentage of population without a health insurance (%)	Hagenlocher et al (2018)
	Percentage of households without any insurance - excl. health insurance (%)	Hagenlocher et al (2018)
Infrastructure and services	Existence of early warning systems (yes/no)	Hagenlocher et al (2018)
	Access to shelter places (density of schools) [index]	Hagenlocher et al (2018)
	Percentage of households without access to waste/water treatment (%)	Hagenlocher et al (2018)
	Drainage system: Average length of drainage network (per km^2)	(Yang et al., 2014)
	Access to emergency places (density of hospitals, fire bridges, police stations)	Hagenlocher et al (2018)
	Density of transportation network: Combined measure of distance to nearest station, density of road and rail networks, density of bus stations and ports for transportation service [index]	Hagenlocher et al (2018)
	Existence of national food reserve (yes/no)	Hagenlocher et al (2018)
	Volume of water storage in a safe reservoir/container (m^3)	Hagenlocher et al (2018)
	Number of hospital beds per 1,000 inhabitants (n)	(Yang et al., 2019)
	Public health expenditure (% of GDP)	Hagenlocher et al (2018)
	Private health expenditure (% of GDP)	Hagenlocher et al (2018)
Adaptive capacity		
Social adaptation	Percentage of population who has experienced hazard(s) in the past 10 years (%)	Hagenlocher et al (2018)
	Fixed assets (per square kilometre)	(Zhang et al., 2017)
	Foreign Direct Investment (% of GDP)	Hagenlocher et al (2018)
	Density of aid projects [index]	Hagenlocher et al (2018)
	Percentage of farmers who use different crop varieties (%)	Hagenlocher et al (2018)
	Number of income-generating activities per household (n)	Hagenlocher et al (2018)
Institutional adaptation	Existence of hazard/vulnerability/risk maps (yes/no)	Hagenlocher et al (2018)
	Existence of adaptation policies/strategies (yes/no)	Hagenlocher et al (2018)
	Existence of integrated development plans: conservation, protection; land use planning (yes/no)	Hagenlocher et al (2018)
	Percentage of GDP spent on innovation and research (%)	Hagenlocher et al (2018)

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Appendix 4 List of the reviewed papers (Chapter 2)

Author	Year	Paper title	Journal	Topic	Ecosystem/ Ecosystem services related
Mansur et al.	2016	An assessment of urban vulnerability in the Amazon Delta and Estuary: a multi-criterion index of flood exposure, socio-economic conditions and infrastructure	Sustainability Science	Assesses the socio-economic vulnerability, considering flood risk exposure, infrastructures and socio-economic sensitivity across urban areas in the Amazon delta	Emphasizes the importance of ecosystem services both in socio-economy and ecological functions
Zhang et al.	2020	Synthetic vulnerability assessment to inform climate-change adaptation along an urbanized coast of Shenzhen, China	Journal of Environmental Management	Integrates biophysical exposure, sensitivity and adaptive capacity into a composite vulnerability index. It aims to identify the most vulnerable areas and key factors related to vulnerability in urban coastal zones.	Adds the role of ecosystem services by using existing ecosystem services model and indicators (InVEST)
Depellegrin et al.	2020	Assessing marine ecosystem services richness and exposure to anthropogenic threats in small sea areas: A case study for the Lithuanian sea space	Ecological Indicators	Presents a geospatial methodology that considering the exposure of human activities for assessing marine ecosystem services. It could identify areas of highest conservation priority and management need.	Uses ecosystem services assessing the SES resources to determine which areas should be given conservation priority; CICES applied
Asmus et al.	2019	The risk to lose ecosystem services due to climate change: A South American case	Ecological Engineering	Applies a qualitative method that assessing ecosystem services value by stakeholders' perception to analyse the environmental risk in coastal areas.	Regards environmental risk as the risk of ecosystem services loss
Willaert et al.	2019	Measuring vulnerability of marine and coastal habitats' potential to deliver ecosystem services:	Frontiers in Marine Science	Utilizes the InVEST model to quantify cumulative habitat risk and calculate a vulnerability index in coastal areas,	Integrates the InVEST habitat risk assessment tool with

		Complex Atlantic region as case study		supporting the development of ecosystem-based management strategies	ecosystem services indicators to create a vulnerability index
Myers et al.	2019	A multidisciplinary coastal vulnerability assessment for local government focused on ecosystems, Santa Barbara area, California	Ocean & Coastal Management	Evaluates the impacts of climate change on watersheds, shorelines, sandy beaches, and coastal wetland ecosystems, offering implications for local government and emphasizing the importance of ecosystem-based solutions in climate change adaptation.	Considers two important coastal ecosystems: sandy beaches and coastal salt marshes
Yanes et al.	2019	Methodological proposal for ecological risk assessment of the coastal zone of Antioquia, Colombia	Ecological Engineering	Assesses ecological risks of 16 coastal ecosystems from 5 environmental threats to explore the application of ecosystem management strategies	Emphasizes risk assessment from the ecosystem perspective: 16 coastal sectors
Khan et al.	2019	An integrated social-ecological assessment of ecosystem service benefits in the Kagera River Basin in Eastern Africa	Regional Environmental Change	Proposes an integrated socio-ecological assessment of ecosystem services in transboundary river basins with broad participation of stakeholders to achieve adaptation planning at the local district level	Considers ecosystem services governance
Silver et al.	2019	Advancing coastal risk reduction science and implementation by accounting for climate, ecosystems, and people	Frontiers in Marine Science	Uses an index-based approach with the role of ecosystem to assess the vulnerability and risk in The Bahamas, seeking to guide decision-makers in implementing nature-based approaches to enhance adaptive capacity	Outlines 5 coastal habitats that offer coastal protection
Bevacqua, Yu and Zhang	2018	Coastal vulnerability: Evolving concepts in understanding vulnerable people and places	Environmental Science & Policy	A review of coastal vulnerability from physical, socio-economic and ecological aspects	Reveals that the assessment of ecological vulnerability primarily relies on evaluating ecosystem services across different scales

Bárcena et al.	2017	Quantifying and mapping the vulnerability of estuaries to point-source pollution using a multi-metric assessment: The Estuarine Vulnerability Index (EVI)	Ecological Indicators	Presents a methodology as a management tool to assess the vulnerability of estuaries	Considers ecological processes and social features related to ecosystem services, incorporating aspects such as naturalness and ecological values
Lilai et al.	2016	A multi-dimensional integrated approach to assess flood risks on a coastal city, induced by sea-level rise and storm tides	Environmental Research Letters	Presents a multidimensional integrated approach to assess coastal flood risks across social-ecological subsystems, aiming to distinguish direct flood risks and consequent indirect risks	Ecological risk is calculated based on the exposure of ecosystem service values to flood risks
Vollmer, Regan and Andelman	2016	Assessing the sustainability of freshwater systems: A critical review of composite indicators	Ambio	Conducts a critical review of indicators for assessing freshwater systems	Uses the notion of ecosystem services for indicator selection
Chung, Kang and Choi	2015	Assessment of coastal ecosystem services for conservation strategies in South Korea	PLoS ONE	Assesses ecosystem services and analyses how ecological, physical and economic factors influence the coastal habitat risk in South Korea	Integrates ecosystem services and social-economic factors into environmental conservation and policy-making processes
Roebeling et al.	2013	Ecosystem service value losses from coastal erosion in Europe: Historical trends and future projections	Journal of Coastal Conservation	Evaluates the extent to which coastal erosion has caused the loss of land cover types and ecosystem service values by combining historical and projected erosion patterns	Utilizes an economic valuation tool to assess ecosystem service values
Narayan et al.	2012	Coastal habitats within flood risk assessments: Role of the 2D SPR approach	Proceedings of the Coastal Engineering Conference	Uses a conceptual framework to assess flood risk, integrating the impact on coastal habitats from both human and ecological factors	Considers the relationship of flood mitigation service and ecological vulnerability

Tuvendal and Elmqvist	2011	Ecosystem services linking social and ecological systems: River brownification and the response of downstream stakeholders	Ecology and Society	A combination of quantitative and qualitative methods to assess the ecosystem service benefits and the brownification impacts on stakeholders	Assesses ecosystem service benefits to represent the ecosystem services that are directly used by human

University of Glasgow

College of Social Sciences

Appendix 5 Indicators selection questionnaire (Chapter 3)

Participant Information Sheet (English version)

Study title: A framework for integrating ecosystem services indicators into vulnerability and risk assessment of deltaic social-ecological systems: Case studies from the Yangtze River Delta and the Pearl River Delta in China
Researcher name: Yuting Peng

Contact email: XXXXXX@student.gla.ac.uk
Research type: Postgraduate Research
School group: School of Interdisciplinary Studies, University of Glasgow

Invitation to participate in the above study
I would like to invite you to take part in a research study. Before you decide to take part it is important for you to understand why the research is being done and what it will involve. Please read the following information carefully and discuss it with others if you wish. Ask the researcher/s if there is anything that is not clear or if you would like more information. Take some time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of this research?
This research aims to design a conceptual framework combined with a modular indicator-based approach to improve the traditional, separated social and ecological indicators methodologies in vulnerability and risk assessments of social-ecological systems. This will be implemented in the Yangtze River Delta and the Pearl River Delta, in order to provide risk profile maps and management options to decision-makers.

What will you do in this research?

Participation in this study is voluntary.

Your participation will involve completing an online questionnaire (**less than 1.5 h**) related to the selection of indicators for vulnerability and risk assessments in the Yangtze River Delta and the Pearl River Delta. Should you be interested in discussing the questionnaire content, I would like to have an online one-on-one interview (**less than 1 h**). The interviews will be audio-recorded and transcribed. The translation will be sent back to you for cross-checking accuracy. This process allows you to ensure that the meaning of what you are trying to say is conveyed in the transcription. It also allows you to reconsider what you said and to add or delate any information. The recording will be deleted once transcription is completed.

The results of online questionnaires and interviews will determine an indicator list, and this final list of indicators will be emailed to each participant. In addition, this list of indicators will be used in subsequent case studies, and the results will be shown in the thesis, publications, and required written summary of results (such as annual progress review, team discussions and academic exchanges, etc.). Other authenticated researchers will have access to the final research data and may use them in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested.

Will your information be kept confidential?

Confidentiality may be limited and conditional – and the researcher has a duty of care to report to the relevant authorities possible harm/danger to the participant or others.

In this research, each participant will be allocated an id number. Then the emails from participants will be deleted. No record of the relationship between the id number and identifiers will be kept. This makes it impossible to identify individuals related to the information sample. All participants will remain anonymous in thesis, publications and required written results. Personal data will be destroyed after the completion of this project (before 2023), and research data will be destroyed after 10 years. All data will be stored in a separate folder on the secure server of University One Drive.

Are there any risks associated with participating in this research?

There are no significant ethical risks involved in this research as we are only asking technical questions related to risks in delta environments. All information provided during the study will be kept confidential. Once the returned files are received, they will be downloaded to a separate folder on University One Drive and the original emails will be deleted. In addition, you do not need to respond to any questions that you do not want to answer, and you can stop filling out the questionnaire or interview at any time.

This project has been considered and approved by the College Research Ethics Committee.

- For further information, please email PGR Yuting Peng: XXXXXX@student.gla.ac.uk
- Supervisors information: Professor Fabrice Renaud: Fabrice.Renaud@glasgow.ac.uk; Dr Natalie Welden: Natalie.Welden@glasgow.ac.uk
- To pursue any complaint about the conduct of the research: contact the College of Social Sciences Ethics Officer, Dr Muir Houston, email: Muir.Houston@glasgow.ac.uk

____________________End of Participant Information Sheet____________________

Consent Form

Title of Project: A framework for integrating ecosystem services indicators into vulnerability and risk assessment of deltaic social-ecological systems: Case studies from the Yangtze River Delta and the Pearl River Delta in China

Name of Researcher: Yuting Peng
Supervisors: Professor Fabrice Renaud; DR Natalie Welden

Please tick as appropriate

Yes ☐ No ☐ I confirm that I have read and understood the Participant Information Sheet for the above study and have had the opportunity to ask questions.

Yes ☐ No ☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

Yes ☐ No ☐ I acknowledge that participants will be referred to by pseudonym.

I understand that:

Yes ☐ No ☐ All names and other material likely to identify individuals will be anonymised.

Yes ☐ No ☐ The material will be treated as confidential and kept in secure storage at all times.

Yes ☐ No ☐ The material will be retained in secure storage for use in future academic research

Yes ☐ No ☐ The material may be used in future publications, both print and online.

Yes ☐ No ☐ I waive my copyright to any data collected as part of this project.

Yes ☐ No ☐ Other authenticated researchers will have access to this data only if they agree to preserve the confidentiality of the information as requested in this form.

Yes ☐ No ☐ Other authenticated researchers may use my words in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form

Yes ☐ No ☐ I acknowledge the provision of a Privacy Notice in relation to this research project.

I agree to take part in this research study ☐

I do not agree to take part in this research study ☐

Name of Participant ………………………… Signature …………………………………………

Date ……………………………………

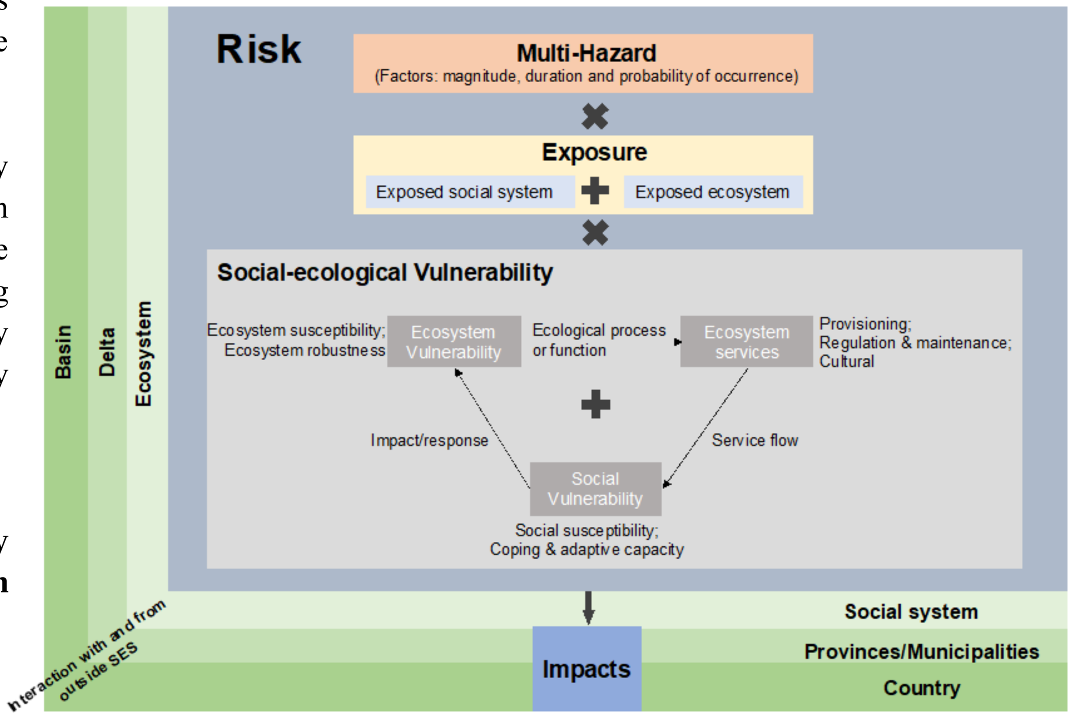
Name of Researcher ……………………………………Signature ………………………………………

Date ……………………………………

Thank you for taking the time to answer these questions. The following tables are about the indicators of vulnerability and risk assessments in the Yangtze River Delta and the Pearl River Delta.

In this research, indicators are grouped according the conceptual vulnerability and risk framework for deltaic social-ecological systems (please see figure on the right), where risk is calculated as Hazard × Exposure × Vulnerability. The vulnerability is a result of ecosystem services (provisioning services, regulating & maintenance services, and cultural services), ecosystem vulnerability (ecosystem susceptibility and ecosystem robustness) and social vulnerability (social susceptibility, coping and adaptive capacity).

The following tables provide an overview of exposure and vulnerability indicators lists that were identified based on the literature. **If you think an indicator needs to be retained, please click the box in the table.**



Conceptual framework for vulnerability and risk assessment of social-ecological systems

Part 1. Your suggestions for indicator selection of the exposure component. For which hazards, if any, are these indicators relevant?

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution			
Exposed ecosystem	Ecosystem exposed to natural hazard (%)	☐	☐	☐	☐	☐	☐	☐	☐	☐
Exposed population	Percentage of population exposed to natural hazard (%)	☐	☐	☐	☐	☐	☐	☐	☐	☐
Exposed economy	Proportion of GDP in primary sector (%)	☐	☐	☐	☐	☐	☐	☐	☐	☐
Exposed infrastructure	Proportion of critical transportation sector: main road, main tunnel, subway, port, airport; Water sector; energy sector; Information and communication sector; civil administration buildings sector (%)	☐	☐	☐	☐	☐	☐	☐	☐	☐

Part 2. Your suggestions for indicator selection of the ecosystem service vulnerability component. Please determine if the indicators could increase [+] or decrease [-] the vulnerability and risk of different hazards. If you have any ideas on indicators, please add them in the Notes column.

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Provisioning service	Volumes of harvested production (ton year^{-1} per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Harvested production of energy crops (ton year^{-1} per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Total water abstraction for public use (m^3 per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Total water abstraction for agriculture and industry use (m^3 per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Groundwater production (recharge rate, mm ha^{-1}year^{-1})	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Rates of surface water drainage (m^3/s)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	The amounts of aquaculture production (kg per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Regulation & Maintenance service	Aggregated index of nutrient recycling potential [index]	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Nitrogen fixation rate (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Gross nitrogen balance (ton year^{-1})	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Average transported sediment at the outlet (ton year^{-1})	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Capacity of ecosystems to avoid soil erosion [dimensionless between 0-1]	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Soil retention (ton ha^{-1} year^{-1})	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Potential increase in agricultural production to compensate the reduction due to the climate change (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Pollination potential [dimensionless between 0-1]	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Species richness	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of protected area (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Undrained habitats, vegetation type and cover (ha per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Carbon-storing habitats (ha per capita)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Forest carbon potential (percent change, %)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Removal of NO_2 by urban vegetation (ton ha^{-1} year^{-1})	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	PM_{10} annual mean concentration (μg m^{-3}); NO_2 annual mean concentration (μg m^{-3});	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
	O_3 value based on daily max 8-h averages ($\mu g\ m^{-3}$)										
	Water quality	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Groundwater quality	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Water Retention Index	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Cultural service	Aggregated index generated through recreation and tourism statistics [index]	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of tourism to GDP (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Intensity of natural and cultural heritage protection based on the number of by number of protected areas overlapping (km^2)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Employment in tourism and other aesthetic activities (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Habitat quality based on common birds [dimensionless ratio]	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Your suggestions to ecosystem service indicators that need to be considered, if there is any:											

Part 3. Your suggestions for indicator selection of the ecosystem vulnerability component, including ecosystem susceptibility and ecosystem robustness. Please determine if the indicators could increase [+] or decrease [-] the vulnerability and risk of different hazards. If you have any ideas on indicators, please add them in the Notes column.

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Ecosystem susceptibility											
Habitat destruction	Percentage of vegetation loss (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Ecosystem susceptibility											
	Percentage of mangrove area loss (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of wetland loss (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of deforested area (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of area covered by "problem soils" (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of shoreline eroded (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Habitat degradation	Increased use of chemicals and fertilisers (qualitative/ quantitative)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Water clarity (Turbidity, Secchi depth)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Normalized Difference Vegetation Index (NDVI)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Land reclamation rate (km^2/year)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Degree of pollution in sediments (heavy metals, etc.) (proxy - concentration of heavy metals in sediments)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Proportion of area covered by algal boom (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Habitat fragmentation	Forest connectivity	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Wetland connectivity	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	River connectivity Proxy indicator: Number of dams and sluice gates per river (per km)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Ecosystem susceptibility											
	River net density (defined as river length divided by land area)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Flooding				
Ecosystem robustness											
Ecosystem & Habitat	Ecosystem Functionality Index (EFI)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Mean Species Abundance (MSA)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of change in land use (agriculture, vegetation, fishery, settlement) (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Number of aquatic environmental reservoirs	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Ecosystem conservation	Percentage of area covered by Wetlands of International Importance (Ramsar Sites) (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of government expenditure on environmental protection (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Policies supporting biodiversity conservation (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Policies for coastal protection (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Participation in treaties, such as Convention on Biological Diversity (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Government expenditure on environmental protection (% expenditure)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Ecosystem restoration	Percentage of nature reserves and wetlands	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Flooding				
Ecosystem robustness											
	Percentage of mangrove area restored (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of forest area restored (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Rate of afforestation area (ha)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Agriculture	Proportion of drought tolerant crops (% of crop production)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percent of area with Intensive/ extensive agriculture in floodplain (% of agriculture land)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Your suggestions to ecosystem vulnerability indicators that need to be considered, if there is any:											

Part 4. Your suggestions for indicator selection of the social vulnerability component, including social susceptibility, coping and adaptive capacity. Please determine if the indicators could increase [+] or decrease [-] the vulnerability and risk of different hazards. If you have any ideas on indicators, please add them in the Notes column.

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Social susceptibility											
Key services	Percentage of households without official land title (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of population without access to (improved) sanitation (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of population without access to clean water (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of population without access to electricity (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of population living in informal settlements (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Social susceptibility											
	Percentage of population living in poorly-constructed houses (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of households that live in rented houses (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	The household proportion with person aged 65 and older (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of reinforced/elevated houses (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of floating houses (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of houses with more than one floor (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of households without access to irrigation (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Human livelihoods	Population density (Population per km^2)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage female-headed households (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Travel time to closest city (mins)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of the population with disabilities (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage malnourished population (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of population with chronic illnesses (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of illiterate population (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Proportion of families below poverty line in total households	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Dependency ratio (%)	+ ☐	+ ☐	+ ☐	+ ☐	+ ☐	+ ☐	+ ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Social susceptibility											
		- ☐	- ☐	- ☐	- ☐	- ☐	- ☐	- ☐			
	GINI index (0-100)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of primary industry to GDP (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Human health & security	Ratio of afforestation coverage areas in the city	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Prevalence of population who experience violence (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Prevalence of population affected by armed conflict (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Number of fatalities caused by terrorists per 10,000 per year	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
Coping capacity											
Individual and household	Per capital GDP per unit area	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Per capita income	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	The average years of education (year)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Ratio of the population with college/university degree or higher	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of households without individual means of transportation	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of households without gross savings (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	Indicator	Hazard setting						Applicable to all hazards	None	I'm not sure	Notes
		Flooding	Cyclones	Storm surge	Drought	Salinity intrusion	Pollution				
	Percentage of households without access to bank loans / (micro-) credits (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Lending interest rate (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of population without a health insurance (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of households without any insurance - excl. health insurance (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Infrastructure and services	Existence of early warning systems (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Access to shelter places (density of schools)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of households without access to waste/water treatment (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Drainage system: Average length of drainage network per km^2	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Access to emergency places (density of hospitals, fire bridges, police stations)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Density of transportation network: Combined measure of distance to nearest station, density of road and rail networks, density of bus stations and ports for transportation service	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Existence of national food reserve (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Volume of water storage in a safe reservoir/container (m^3)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Number of hospital beds per 1,000 inhabitants	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Public health expenditure (% of GDP)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Private health expenditure (% of GDP)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	

Category	**Indicator**	**Hazard setting**						**Applicable to all hazards**	**None**	**I'm not sure**	**Notes**
		Flooding	**Cyclones**	**Storm surge**	**Drought**	**Salinity intrusion**	**Pollution**				
Adaptive capacity											
Social adaption	Percentage of population who has experienced hazard(s) in the past 10 years (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Fixed assets per square kilometre	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Foreign Direct Investment (% of GDP)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Density of aid projects	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of farmers who use different crop varieties (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Number of income-generating activities per household (number)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Institutional adaption	Existence of hazard/vulnerability/risk maps (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Existence of adaptation policies/strategies (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Existence of integrated development plans: conservation, protection; land use planning (yes/no)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
	Percentage of GDP spent on innovation and research (%)	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	+ ☐ - ☐	☐	☐	
Your suggestions to social vulnerability indicators that need to be considered, if there is any:											

Part 5. Your suggestions to additional indicators that need to be considered, if there is any

If you are interested to discuss some issues with the researcher through online interviews (e.g. Zoom, Teams or Wechat), please click the box. ☐

University of Glasgow

College of Social Sciences

Appendix 6 Weights selection questionnaire (Chapter 3)

The JISC online survey tool was used for Weights Selection Questionnaire. This appendix is adapted from the online survey version.

Participant Information Sheet (English version)

Study title: A framework for integrating ecosystem services indicators into vulnerability and risk assessment of deltaic social-ecological systems: Case studies from the Yangtze River Delta and the Pearl River Delta in China
Researcher name: Yuting Peng

Contact email: XXXXXX@student.gla.ac.uk
Research type: Postgraduate Research
School group: School of Interdisciplinary Studies, University of Glasgow

Invitation to participate in the above study

I would like to invite you to take part in a research study. Before you decide to take part it is important for you to understand why the research is being done and what it will involve. Please read the following information carefully and discuss it with others if you wish. Ask the researcher/s if there is anything that is not clear or if you would like more information. Take some time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of this research?

This research aims to design a conceptual framework combined with a modular indicator-based approach to improve the traditional, separated social and ecological indicators methodologies in vulnerability and risk assessments of social-ecological systems. This will be implemented in the Yangtze River Delta and the Pearl River Delta, in order to provide risk profile maps and management options to decision-makers.

What will you do in this research?

Participation in this study is voluntary.

You have already participated in this research project by completing an initial questionnaire, you are now being asked to answer some additional follow-up questions specifically about weighing the determined indicator lists. Your participation will involve completing an online questionnaire (**less than 1 h**) related to the weights selection of indicators for vulnerability and risk assessments in the Yangtze River Delta and the Pearl River Delta.

The results of the online questionnaire will determine the weights for the indicator list. In addition, the result after summarizing will be used in subsequent case studies, and the results will be shown in the thesis, publications, and required written summary of results (such as annual progress review, team discussions and academic exchanges, etc.). Other authenticated researchers will have access to the final research data and may use them in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested.

Will your information be kept confidential?

Confidentiality may be limited and conditional – and the researcher has a duty of care to report to the relevant authorities possible harm/danger to the participant or others.

In this research, each participant will be allocated an id number. Then the emails from participants will be deleted. No record of the relationship between the id number and identifiers will be kept. This makes it impossible to identify individuals related to the information sample. All participants will remain anonymous in thesis, publications and required written results. Personal data will be destroyed after the completion of this project (before 2023), and research data will be destroyed after 10 years. All data will be stored in a separate folder on the secure server of University One Drive.

Are there any risks associated with participating in this research?

There are no significant ethical risks involved in this research as we are only asking technical questions related to risks in delta environments. All information provided during the study will be kept confidential. Once the returned files are received, they will be downloaded to a separate folder on University One Drive and the original emails will be deleted. In addition, you do not need to respond to any questions that you do not want to answer, and you can stop filling out the questionnaire or interview at any time.

This project has been considered and approved by the College Research Ethics Committee.

- For further information, please email PGR Yuting Peng: XXXXXX@student.gla.ac.uk
- Supervisors information: Professor Fabrice Renaud: Fabrice.Renaud@glasgow.ac.uk; Dr Natalie Welden: Natalie.Welden@glasgow.ac.uk
- To pursue any complaint about the conduct of the research: contact the College of Social Sciences Lead for Ethical Review, Dr Susan Batchelor: email socsci-ethics-lead@glasgow.ac.uk

____________________End of Participant Information Sheet____________________

Consent Form

I confirm that I have read and understood the Participant Information Sheet for the above study and have had the opportunity to ask questions.

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

I acknowledge that participants will be referred to by pseudonym.

All names and other material likely to identify individuals will be anonymised.

The material will be treated as confidential and kept in secure storage at all times.

The material will be retained in secure storage for use in future academic research.

The material may be used in future publications, both print and online.

I agree to waive my copyright to any data collected as part of this project.

I understand that other authenticated researchers will have access to this data only if they agree to preserve the confidentiality of the information as requested in this form.

I understand that other authenticated researchers may use my words in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form.

I acknowledge the provision of a Privacy Notice in relation to this research project.
Please tick as appropriate:

I agree to take part in this research study ☐

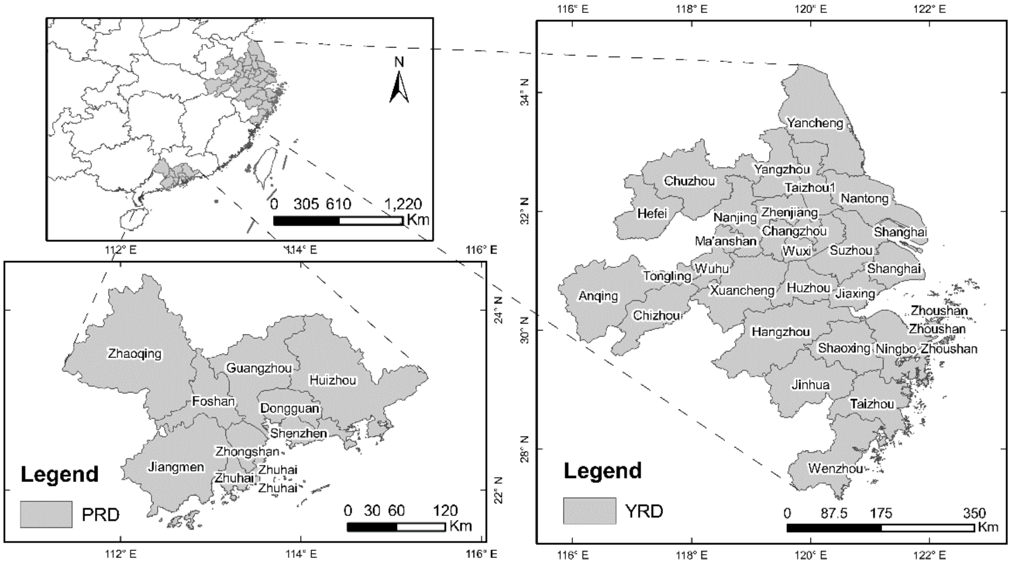
I do not agree to take part in this research study ☐

Company, Agency, or Institution Name ……………………………………

Email Address (if you want to receive the results) ………………………………………

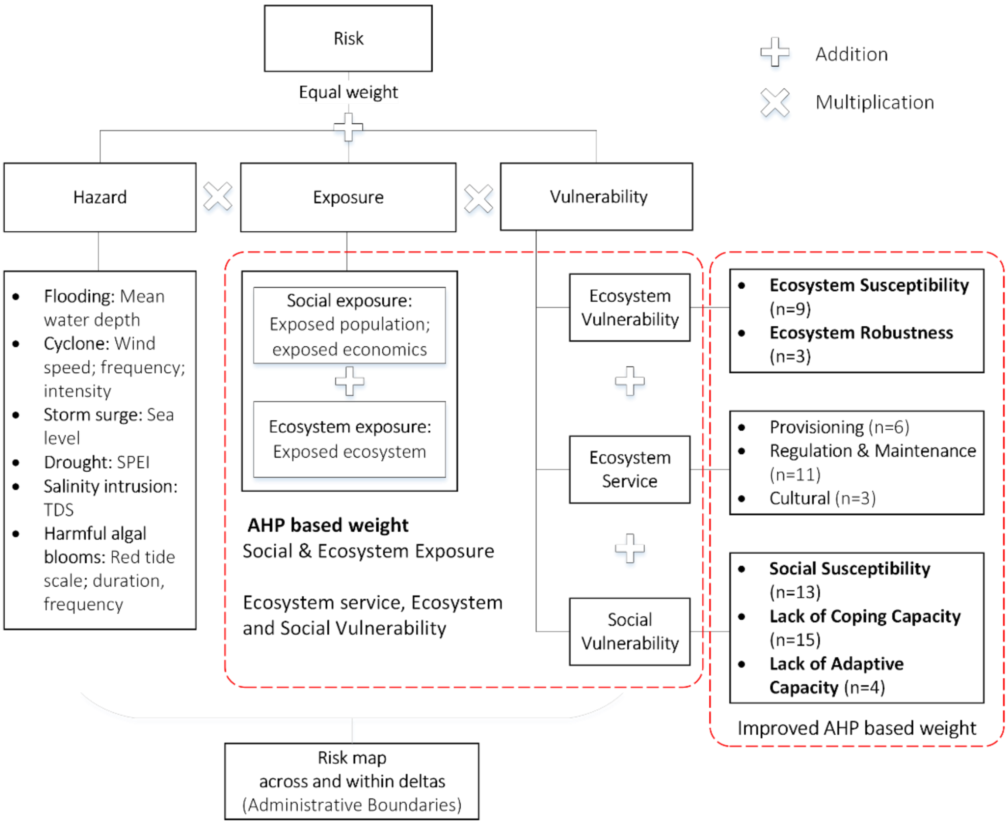
1. Study area

This study was conducted in the Yangtze River Delta (YRD) and Pearl River Delta (PRD), two of China's fastest-growing economic and population-centred regions. They are coastal areas with a geographic range between 27.05°-33.38°N, 117.05°-123.42°E, and 21.45°-23.05°N, 112.47°-114.88°E respectively.



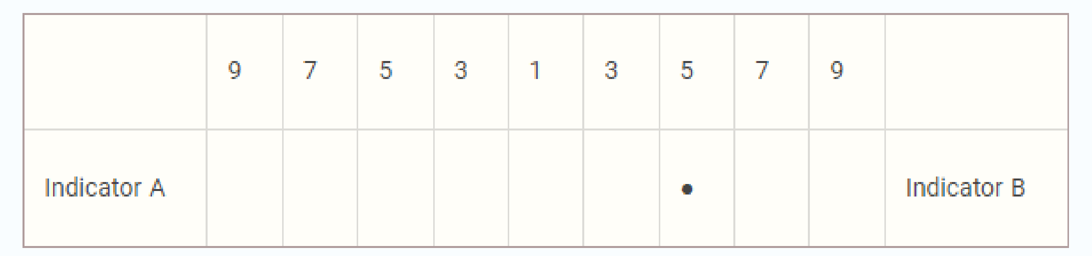
2. Method

This study applies a comprehensive research framework for deltaic vulnerability and risk assessment (please see the following figure), where risk is calculated as Hazard × Exposure × Vulnerability.



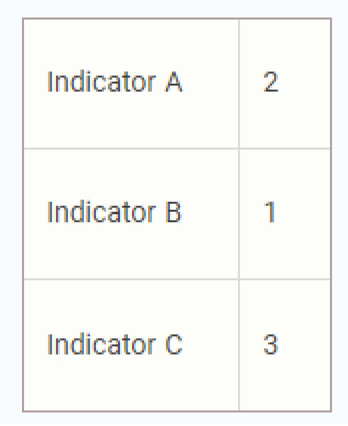
We plan to weigh the risk components using a combination of analytic hierarchy process (AHP) and improved analytic hierarchy process (IAHP).

For the exposure and vulnerability subcomponents (indicators ≤4), we take the traditional AHP approach to develop pairwise comparison matrices for each component. 1= Equal, 3= Moderate, 5= Strong, 7= Very strong, 9= Extreme. In the following example, **Indicator B** is judged as being more important when compared to **Indicator A** since the selected scale of 5 is on the side of Indicator B.



	9	7	5	3	1	3	5	7	9	
Indicator A							●			Indicator B

An improved AHP (IAHP) is adopted to weigh the criteria of all vulnerability sub-components (within ecosystem vulnerability, ecosystem service and social vulnerability), which is to change the pairwise comparison to the ranking of the elements. Sorting all indicators using the scale: 1 (least important) - n (most important). If the indicators are considered equally important, they can be assigned the same number. In the following example, **Indicator C** is judged as the most important, **Indicator B** is the least important, and **Indicator A** is between **Indicator C** and **Indicator B** in terms of importance.



Indicator A	2
Indicator B	1
Indicator C	3

An eigenvector will be calculated according to the comparison matrix, which is the final weight distribution. Following the modular framework, the (multi-)hazard, exposure and vulnerability of the deltaic SES will be aggregated by multiplicative aggregation into a (multi-hazard) risk index

3. Exposure component

Compare the relative importance with respect to Exposure component (Components: Exposed population, Exposed economic activities, Exposed ecosystem). Choose one number per row using the scale: 1= Equal importance, 3= Moderate importance, 5= Strong importance, 7= Very strong importance, 9= Extreme importance.

	9	7	5	3	1	3	5	7	9	
Exposed population										Exposed economics
Exposed population										Exposed ecosystem
Exposed economics										Exposed ecosystem

4. Vulnerability component

Compare the relative importance with respect to Vulnerability component (Components: Ecosystem vulnerability, Ecosystem service, Social vulnerability). Choose one number per row using the scale: 1= Equal importance, 3= Moderate importance, 5= Strong importance, 7= Very strong importance, 9= Extreme importance.

	9	7	5	3	1	3	5	7	9	
Ecosystem vulnerability										Ecosystem service
Ecosystem vulnerability										Social vulnerability
Ecosystem service										Social vulnerability

4.1 Ecosystem vulnerability

Compare the relative importance with respect to Ecosystem vulnerability component (Components: Ecosystem Susceptibility and Ecosystem Robustness). Choose one number per row using the scale: 1= Equal importance, 3= Moderate importance, 5= Strong importance, 7= Very strong importance, 9= Extreme importance. Note: Ecosystem robustness mainly refers to conservation practices in this study.

	9	7	5	3	1	3	5	7	9	
Ecosystem Susceptibility										Ecosystem robustness

4.1.1 Ecosystem Susceptibility

Compare the relative importance with respect to Ecosystem Susceptibility indicators. Sorting all indicators using the scale: 1 (least important) - 9 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-9)**
% of deforested area	
% of wetland loss	

% of area covered by "problem soils"	
Increased use of chemicals and fertilisers	
Normalized Difference Vegetation Index (NDVI)	
% of area covered by algal boom (%)	
Forest connectivity	
Wetland connectivity	
River connectivity	

4.1.2 Ecosystem Robustness

Compare the relative importance with respect to Ecosystem Robustness indicators. Sorting all indicators using the scale: 1 (least important) - 3 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-2)**
% of government expenditure on environmental protection	
% of area of nature reserves	

4.2 Ecosystem service

Compare the relative importance with respect to Ecosystem service component (Components: Provisioning. Regulation & Maintenance Cultural). Choose one number per row using the scale: 1= Equal importance, 3= Moderate importance, 5= Strong importance, 7= Very strong importance, 9= Extreme importance.

	9	7	5	3	1	3	5	7	9	
Provisioning										Regulation & Maintenance
Provisioning										Cultural
Regulation & Maintenance										Cultural

4.2.1 Provisioning service

Compare the relative importance with respect to Provisioning service indicators. Sorting all indicators using the scale: 1 (least important) - 6 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-6)**
Biomass (agriculture): Volumes of harvested production	
Biomass (aquaculture): The amounts of aquaculture production	
Biomass (forestry): Harvested production of energy crops	
Water resource : Total groundwater recharge	
Water use: Total water abstraction for public use	
Water use: Total water abstraction for agriculture and industry use	

4.2.2 Regulation & Maintenance service

Compare the relative importance with respect to Regulation & Maintenance service indicators. Sorting all indicators using the scale: 1 (least important) - 12 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-12)**
Soil quality regulation: Total nitrogen	
Soil quality regulation: Soil organic carbon stock	
Soil quality regulation: Cation exchange capacity	
Erosion regulation: Capacity of ecosystem to avoid soil erosion Proxy indicator: Total soil loss from soil erosion	
Pollination: Pollination potential [index]	

Proxy indicator: Potential demand of crop production on bee pollination	
Biodiversity: Biodiversity Intactness Index	
Mean Species Abundance	
Natural hazard protection: % of windbreaks Proxy indicator: Green space rate of built district (%)	
Air quality regulation: Air Quality Index	
Climate regulation: Forest carbon potential (%)	
Water regulation: Water retention index	
Water regulation: Water quality	

4.2.3 Cultural service

Compare the relative importance with respect to Cultural service indicators. Sorting all indicators using the scale: 1 (least important) - 3 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-3)**
Tourism: % of tourism to GDP	
Recreation: Share of high provision easily accessible land in the recreation opportunity spectrum (%) Proxy indicator: Public recreational park green space	
Aesthetic: Employment of tourism in A level scenic spot (%) Note: The quality level of tourist attractions is divided into five levels, from high to low, they are AAAAA, AAAA, AAA, AA, and A-level.	

4.3 Social vulnerability

Compare the relative importance with respect to Social vulnerability component (Components: Social Susceptibility, Lack of coping capacity, Lack of adaptive capacity). Choose one number per row using the scale: 1= Equal importance, 3= Moderate importance, 5= Strong importance, 7= Very strong importance, 9= Extreme importance.

	9	7	5	3	1	3	5	7	9	
Social Susceptibility										Lack of coping capacity
Social Susceptibility										Lack of adaptive capacity
Lack of coping capacity										Lack of adaptive capacity

4.3.1 Social Susceptibility

Compare the relative importance with respect to Social Susceptibility indicators. Sorting all indicators using the scale: 1 (least important) - 13 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-13)**
% of population without access to (improved) sanitation	
% of population without access to clean water	
% of households without access to irrigation (%)	
The household proportion with person aged 65 and older (%)	
Population density	
% of female-headed households Proxy indicator: % of female population	
Travel time to closest city Proxy indicator: % of rural population	
% of the population with disabilities	
% of malnourished population	

Proxy indicator: % of underweight children under the age of five	
% of illiterate population	
% of families below the poverty line in total households	
Dependency ratio	
% of contribution of primary industry to GDP	

4.3.2 Coping capacity

Compare the relative importance with respect to Coping capacity indicators. Sorting all indicators using the scale: 1 (least important) - 15 (most important). If the indicators are considered equally important, they can be assigned the same number.

Indicator	**Rank (1-15)**
Per capital GDP	
The average years of education	
% of households without individual means of transportation	
% of households without gross savings Proxy indicator: Disposable income per capita	
% of households without access to bank loans / (micro-) credits Proxy indicator: Loans per capita	
% of population without a health insurance (%)	
Access to shelter places Proxy indicator: Density of schools	
Access to emergency places Proxy indicator: Density of hospitals	
% of households without access to water treatment	
Drainage system	
Density of transportation network	
Water storage in a safe reservoir/container	
Number of hospital beds per 1,000 inhabitants	
Public health expenditure (% of GDP)	
Private health expenditure (% of GDP)	

4.3.3 Adaptive capacity

Compare the relative importance with respect to Adaptive capacity indicators. Sorting all indicators using the scale: 1 (least important) - 3 (most important). If the indicators are considered equally important, they can be assigned the same number. NOTE: Fixed asset investment means the dollar amount invested in building, land, machinery and equipment, and infrastructure related to the project.

Indicator	**Rank** **(1-3)**
Fixed assets Proxy indicator: Fixed assets investment per square kilometre	
Existence of integrated development plans (yes/no) Proxy indicator: % of Disaster Prevention and Emergency Management Expenditure	
% of GDP spent on research and development	

5. Do you have any other comments, questions, or concerns?

Appendix 7 Data sources (Chapter 3)

Appendix 7 provides the indicator list and associated data sources that were used for two case study deltas.

Hazard and Exposure

Hazard Flooding		**Indicator** Mean water depth (in m)				**Code** H_FLO
Exposure		**Social Exposure**			**Ecosystem Exposure**	
		Indicator Percentage of population exposed to flooding (%); Percentage of economics exposed to flooding (%)	**Code** E_S_POP_ FLO; E_S_ECO_ FLO		**Indicator** Ecosystem exposed to flooding (%)	**Code** E_E_ FLO
Delta		**Yangtze River Delta**				**Pearl River Delta**
		Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Hazard	Flood hazard map: (Francesco et al., 2016) Key literature: (Dottori et al., 2016)				
	Exposure	Population: (WorldPop, 2018) Economic: (Xinliang, 2017) Land cover: GlobeLand30				
Year	Hazard	Return period: 10, 20, 50, 100, 500 years				
	Exposure	Population: 2020 Economics: 2019 Land cover: 2020				
Scale	Hazard	Municipality	City	City	City	City
	Exposure	Municipality	City	City	City	City
URL		Hazard: https://data.jrc.ec.europa.eu/collection/id-0054 Population: https://www.worldpop.org/ Economics: http://www.resdc.cn/DOI				

	Land cover: http://www.globallandcover.com/home_en.html
Data acquisition and creation	Hazard: In this study, return period of 10, 20, 50, 100, and 500 years are considered, where cell values indicate water depth (in m). The average water depth of each administrative unit was calculated through GIS tool (ArcMap 10.8) based on the hazard map of each return period, and then the mean value of each return period was taken as the hazard data. A higher value corresponds to a more severe flooding degree. After taking into account the data features and the aim of constructing a composite indicator, the rescaling (min-max normalization) method was applied to redistribute the indicator to a range with an average of zero and a standard deviation of one. Exposure: Spatial hazard maps represent areas potentially affected by floods. We used the Raster Calculator of ArcMap 10.8 to calculate a flooding exposure map, where areas with no water depth data were set to 0 and other areas (potentially exposed to flooding) were set to 1. % of the population exposed to flooding: Combined with the gridded population data, the spatial distribution of the population exposed to flooding is the product of the population map and the exposure map obtained in the previous step. % of the population exposed to flooding was measured by calculating the population exposed to flooding as a percentage of the total population of the study area. Assuming an even regional spatial population distribution, and the mean value of each administrative unit was taken as the population. % of economics exposed to flooding: Similar to calculating the percentage of the population exposed to flooding, the gridded economic data (GDP) are used. The % of economics exposed to flooding was calculated as the economics exposed to flooding as a percentage of the total economics of the study area. Ecosystem exposed to flooding (%): GlobeLand30 includes 10 land cover classes in total, namely cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surface, bare land, perennial snow and ice. We excluded the three classes of artificial surface, bare land, perennial snow and ice (assigned a value of 0), and set the other areas as ecosystems and assigned a value of 1. The other steps are similar to the above, the ecosystem exposed to flooding was represented by the percentage of area of each administrative unit exposed to flooding.

<table>
<tr><td>Hazard
Cyclones</td><td colspan="3">Indicator
Wind speed (km/h); Cyclone frequency</td><td>Code
H_CYC_WIN;
H_CYC_FRE</td></tr>
<tr><td rowspan="2">Exposure</td><td colspan="2">Social Exposure</td><td colspan="2">Ecosystem Exposure</td></tr>
<tr><td>Indicator
Percentage of population exposed to cyclones (%);</td><td>Code
E_S_POP_ CYC;
E_S_ECO_ CYC</td><td>Indicator
Ecosystem exposed to cyclones (%)</td><td>Code
E_E_ CYC</td></tr>
</table>

		Percentage of economics exposed to cyclones (%)				
Delta		**Yangtze River Delta**				**Pearl River Delta**
		Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Hazard	Global Risk Data Platform				
	Exposure	Population: (WorldPop, 2018) Economic: (Xinliang, 2017) Land cover: GlobeLand30				
Year	Hazard	1970 - 2009				
	Exposure	Population: 2020 Economics: 2019 Land cover: 2020				
Scale	Hazard	Municipality	City	City	City	City
	Exposure	Municipality	City	City	City	City
URL		Hazard: http://preview.grid.unep.ch Population: https://www.worldpop.org/ Economics: http://www.resdc.cn/DOI Land cover: http://www.globallandcover.com/home_en.html				
Data acquisition and creation		Hazard: In this study, an integrated cyclone map was considered, where cell values indicate wind speed (in km/h). The average wind speed of each administrative unit was calculated through GIS tool (ArcMap 10.8) based on the hazard map. The higher the value, the more severe the hazard is. After taking into account the data features and the aim of constructing a composite indicator, the rescaling (min-max normalization) method was applied to redistribute the indicator to a range with an average of zero and a standard deviation of one. Note: the added link has been updated and different return period maps (from 1-in-50-year to 1-in-1000-year) are provided, which can be calculated using the same steps as for flooding hazard. The original map could be available via personal request. Exposure: We used the Raster Calculator of ArcMap 10.8 to process the spatial cyclone frequency map provided by the Global Risk Data Platform, where areas with value 0 were kept at the original value of 0 and other areas (potentially exposed to cyclone) were set to 1. The newly obtained map was used to represent areas potentially affected by cyclones, and can be used to assess the exposure of population, economics and ecosystems to cyclones. % of the population exposed to cyclones: Combined with the gridded population data, the spatial distribution of the population exposed to cyclones is the product of the population map and the exposure map obtained in the previous step. % of the population exposed tocyclonese was measured by calculating the population exposed to cyclone as a percentage of the total population of the study area. Assuming an even regional spatial population distribution, each administrative unit's mean value was taken as the				

	population. % of economics exposed to cyclones: Similar to calculating the percentage of the population exposed to cyclone, the gridded economic data (GDP) are used. The % of economics exposed to cyclones was calculated as the economics exposed to cyclones as a percentage of the total economics of the study area. Ecosystem exposed to cyclones (%): GlobeLand30 includes 10 land cover classes in total, namely cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surface, bare land, perennial snow and ice. We excluded the three classes of artificial surface, bare land, perennial snow and ice (assigned a value of 0), and set the other areas as ecosystems and assigned a value of 1. The other steps are similar to the above, the ecosystem exposed to cyclones was represented by the percentage of area of each administrative unit exposed to cyclone.

<table>
<tr><td colspan="2">Hazard
Storm surge
(Coastal flooding)</td><td colspan="4">Indicator
Sea levels (in m)</td><td>Code
H_STO</td></tr>
<tr><td colspan="2" rowspan="2">Exposure</td><td colspan="3">Social Exposure</td><td colspan="2">Ecosystem Exposure</td></tr>
<tr><td>Indicator
Percentage of population exposed to storm surge (%);
Percentage of economics exposed to storm surge (%)</td><td colspan="2">Code
E_S_POP_ STO;
E_S_ECO_ STO</td><td>Indicator
Ecosystem exposed to storm surge (%)</td><td>Code
E_E_ STO</td></tr>
<tr><td colspan="2" rowspan="2">Delta</td><td colspan="4">Yangtze River Delta</td><td rowspan="2">Pearl River Delta</td></tr>
<tr><td>Shanghai</td><td>Jiangsu</td><td>Zhejiang</td><td>Anhui</td></tr>
<tr><td rowspan="2">Source</td><td>Hazard</td><td colspan="5">(Muis et al., 2016)</td></tr>
<tr><td>Exposure</td><td colspan="5">Population: (WorldPop, 2018)
Economic: (Xinliang, 2017)
Land cover: GlobeLand30</td></tr>
<tr><td rowspan="2">Year</td><td>Hazard</td><td colspan="5">Return period: 10, 25, 50, 100, 250, 500, 1000 years</td></tr>
<tr><td>Exposure</td><td colspan="5">Population: 2020
Economics: 2019
Land cover: 2020</td></tr>
<tr><td rowspan="2">Scale</td><td>Hazard</td><td>Municipality</td><td>City</td><td>City</td><td>City</td><td>City</td></tr>
<tr><td>Exposure</td><td>Municipality</td><td>City</td><td>City</td><td>City</td><td>City</td></tr>
</table>

URL	Hazard: https://www.geonode-gfdrrlab.org/; https://doi.org/10.1038/ncomms11969 Population: https://www.worldpop.org/ Economics: http://www.resdc.cn/DOI Land cover: http://www.globallandcover.com/home_en.html
Data acquisition and creation	Hazard: In this study, return period of 10, 25, 50, 100, 250, 500, and 1000 years are considered, where cell values indicate sea levels (in m). The average sea levels of each administrative unit was calculated through GIS tool (ArcMap 10.8) based on the hazard map of each return period, and then the mean value of each return period was taken as the hazard data. The higher the extreme sea levels, the greater the potential coastal flood hazard. After taking into account the data features and the aim of constructing a composite indicator, the rescaling (min-max normalization) method was applied to redistribute the indicator to a range with an average of zero and a standard deviation of one. Exposure: Spatial hazard maps represent areas potentially affected by storm surges (inundation extent). We used the Raster Calculator of ArcMap 10.8 to calculate an exposure map, where areas with no sea levels data were set to 0 and other areas (potentially exposed to coastal flooding) were set to 1. % of the population exposed to storm surge: Combined with the gridded population data, the spatial distribution of the population exposed to storm surge is the product of the population map and the exposure map obtained in the previous step. % of the population exposed to storm surge was measured by calculating the population exposed to storm surge as a percentage of the total population of the study area. Assuming an even regional spatial population distribution, and the mean value of each administrative unit was taken as the population. % of economics exposed to storm surge: Similar to calculating the percentage of the population exposed to storms, gridded economic data (GDP) are used. The % of economics exposed to storm surge was calculated as the economics exposed to storm surge as a percentage of the total economics of the study area. Ecosystem exposed to storm surge (%): GlobeLand30 includes 10 land cover classes in total, namely cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surface, bare land, perennial snow and ice. We excluded the three classes of artificial surface, bare land, perennial snow and ice (assigned a value of 0), and set the other areas as ecosystems and assigned a value of 1. The other steps are similar to the above, the ecosystem exposed to storm surge was represented by the percentage of area of each administrative unit exposed to storm surge.

Hazard Drought	**Indicator** Standardized precipitation evapotranspiration index (SPEI)		**Code** H_DRO
Exposure	**Social Exposure**	**Ecosystem Exposure**	

		Indicator Percentage of population exposed to drought (%); Percentage of economics exposed to drought (%)	**Code** E_S_POP_DRO; E_S_ECO_DRO		**Indicator** Ecosystem exposed to drought (%)	**Code** E_E_DRO
Delta		**Yangtze River Delta**				**Pearl River Delta**
		Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Hazard	EAR5 dataset; (Vicente-Serrano et al., 2010)				
	Exposure	Population: (WorldPop, 2018) Economic: (Xinliang, 2017) Land cover: GlobeLand30				
Year	Hazard	1979-2020				
	Exposure	Population: 2020 Economics: 2019 Land cover: 2020				
Scale	Hazard	Municipality	City	City	City	City
	Exposure	Municipality	City	City	City	City
URL		Hazard: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 Population: https://www.worldpop.org/ Economics: http://www.resdc.cn/DOI Land cover: http://www.globallandcover.com/home_en.html				
Data acquisition and creation		Calculation processes are based on Vicente-Serrano et al. (2010)				

Hazard Salinity intrusion	**Indicator** Salinity (Proxy: TDS concentrations) (mg/l)				**Code** H_SAL
Exposure	**Social Exposure**			**Ecosystem Exposure**	
	Indicator Percentage of population exposed to salinity intrusion (%); Percentage of economics exposed to salinity intrusion (%)	**Code** E_S_POP_ SAL; E_S_ECO_ SAL		**Indicator** Ecosystem exposed to salinity intrusion (%)	**Code** E_E_ SAL
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	

Source	Hazard	(van Vliet et al., 2021)				
	Exposure	Population: (WorldPop, 2018) Economic: (Xinliang, 2017) Land cover: GlobeLand30				
Year	Hazard	1979-2010				
	Exposure	Population: 2020 Economics: 2019 Land cover: 2020				
Scale	Hazard	Municipality	City	City	City	City
	Exposure	Municipality	City	City	City	City
URL		Hazard: https://doi.org/10.1088/1748-9326/abbfc3 (personal request) Population: https://www.worldpop.org/ Economics: http://www.resdc.cn/DOI Land cover: http://www.globallandcover.com/home_en.html				
Data acquisition and creation		Hazard: Since no public data on salinity/saltwater intrusion (such as salinity content) for the study area, an available gridded global total dissolved solids (TDS) dataset based on water quality modelling was used to draw the comparative study. We contacted the author (van Vliet) via personal communication to obtain the global map of total dissolved solids to compare salinity in the study area. According to the salinity intrusion (salt tide) data in Hangzhou from the Zhejiang Marine Disaster Bulletin 2018, 2019 and 2020 (DNR, 2020) and the quantile classification method, a reclassification of the TDS map was conducted by removing values less than 66 mg/l, then enabling the estimate of the potentially exposed area. The average TDS of each administrative unit was calculated through GIS tool (ArcMap 10.8) based on the hazard map. A higher TDS value corresponds to a more severe salinity intrusion degree. After taking into account the data features and the aim of constructing a composite indicator, the rescaling (min-max normalization) method was applied to redistribute the indicator to a range with an average of zero and a standard deviation of one. Exposure: Spatial hazard maps represent areas potentially affected by salinity intrusion. We used the Raster Calculator of ArcMap 10.8 to calculate a salinity intrusion exposure map, where areas with no water depth data were set to 0 and other areas (potentially exposed to salinity intrusion) were set to 1. % of the population exposed to salinity intrusion: Combined with the gridded population data, the spatial distribution of the population exposed to salinity intrusion is the product of the population map and the exposure map obtained in the previous step. % of the population exposed to salinity intrusion was measured by calculating the population exposed to salinity intrusion as a percentage of the total population of the study area. Assuming an even regional spatial population distribution, and the mean				

	value of each administrative unit was taken as the population. % of economics exposed to salinity intrusion: Similar to calculating the percentage of the population exposed to salinity intrusion, the gridded economic data (GDP) are used. The % of economics exposed to salinity intrusion was calculated as the economics exposed to salinity intrusion as a percentage of the total economics of the study area. Ecosystem exposed to salinity intrusion (%): GlobeLand30 includes 10 land cover classes in total, namely cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surface, bare land, perennial snow and ice. We excluded the three classes of artificial surface, bare land, perennial snow and ice (assigned a value of 0), and set the other areas as ecosystems and assigned a value of 1. The other steps are similar to the above, the ecosystem exposed to salinity intrusion was represented by the percentage of area of each administrative unit exposed to salinity intrusion.

Vulnerability Domain

Social Vulnerability

Social Susceptibility			
Theme Key Services	**Code** SS1	**Indicator** Percentage of population without access to clean water (%)	**Measuring unit/proxy indicator** Percentage of population without access to clean water (%)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+

Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	City	Province
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/

Data acquisition and creation	Census data

Social Susceptibility			
Theme Key Services	**Code** SS2	**Indicator**	**Measuring unit/proxy indicator**

		Percentage of households without access to irrigation (%)		Percentage of area not equipped for irrigation (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	Not relevant	Not relevant	Not relevant	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Siebert et al., 2013)				
Year	2013	2013	2013	2013	2013
Scale	Municipality	City	City	City	City
URL	https://www.fao.org/aquastat/en/				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_4	**Indicator** Population density (Population per km^2)		**Measuring unit/proxy indicator** Population density (Population per km^2)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	

Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_6	**Indicator** Travel time to closest city (mins)		**Measuring unit/proxy indicator** Percentage of rural population (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	Not relevant	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Social Susceptibility			
Theme Human Livelihoods	**Code** SS_5	**Indicator** Percentage female-headed households (%)	**Measuring unit/proxy indicator** Percentage female population (%)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	Not relevant	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	City	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Social Susceptibility			
Theme Human Livelihoods	**Code** SS_3	**Indicator** The household proportion with person aged 65 and older (%)	**Measuring unit/proxy indicator** The household proportion with person aged 65 and older (%)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	Yangtze River Delta				Pearl River Delta
	Shanghai	Jiangsu	Zhejiang	Anhui	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Zhejiang Provincial Bureau of Statistics	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2020	2020	2019	2020
Scale	Municipality	City	Province	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	http://tjj.zj.gov.cn/art/2021/5/13/art_1229129205_4632764.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/tjgb/content/post_3283432.html
Data acquisition and creation	Census data				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_7	**Indicator** Percentage malnourished population (%)		**Measuring unit/proxy indicator** Percentage underweight children under the age of five (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Health Commission of China				
Year	2017	2017	2017	2017	2017
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Health Statistical Yearbook 2019				
Data acquisition and creation	Census data				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_8	**Indicator** Percentage of illiterate population (%)		**Measuring unit/proxy indicator** Percentage of illiterate population (%)	
Hazard	Flooding	Cyclone	Storm Surge	Drought	Salinity intrusion

			(Coastal flooding)		
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Health Commission of China	National Health Commission of China	National Health Commission of China	Statistics Bureau of Anhui Province	National Health Commission of China
Year	2017	2017	2017	2017	2017
Scale	Municipality	Province	Province	City	Province
URL	N/A China Health Statistical Yearbook 2019	N/A China Health Statistical Yearbook 2019	N/A China Health Statistical Yearbook 2019	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	N/A China Health Statistical Yearbook 2019
Data acquisition and creation	Census data				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_10	**Indicator** Dependency ratio (%)		**Measuring unit/proxy indicator** Dependency ratio (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2017	2017	2019	2019
Scale	Municipality	Province	Province	City	Province

URL	http://www.stats.gov.cn/tjsj/ndsj/	http://www.stats.gov.cn/tjsj/ndsj/	http://www.stats.gov.cn/tjsj/ndsj/	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_9	**Indicator** Percentage of families below the poverty line in total households (%)		**Measuring unit/proxy indicator** Percentage of population below the poverty line in rural areas (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China				
Year	2014	2014	2014	2014	2014
Scale	Municipality	Province	Province	Province	Province
URL	N/A Poverty Monitoring Report of Rural China 2019				
Data acquisition and creation	Census data				

Social Susceptibility					
Theme Human Livelihoods	**Code** SS_11	**Indicator** Percentage of contribution of primary industry to GDP (%)		**Measuring unit/proxy indicator** Percentage of contribution of primary industry to GDP (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				

	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	**Pearl River Delta**
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Zhejiang Provincial Bureau of Statistics	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	http://tjj.zj.gov.cn/art/2021/5/13/art_1229129205_4632764.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Coping Capacity					
Theme	**Code**	**Indicator**	**Measuring unit/proxy indicator**		
Individual and Household	CC1	Per Capita GDP	Per Capita GDP (yuan)		
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Zhejiang Provincial Bureau of Statistics	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	http://tjj.zj.gov.cn/art/2021/5/13/art_1229129205_4632764.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/

Data acquisition and creation	Census data

Coping Capacity					
Theme Individual and Household	**Code** CC2	**Indicator** The average years of education (year)		**Measuring unit/proxy indicator** The average years of education (year)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	National Bureau of Statistics of China	National Bureau of Statistics of China	Statistics Bureau of Anhui Province	National Bureau of Statistics of China
Year	2020	2020	2020	2020	2020
Scale	Municipality	Province	Province	City	Province
URL	N/A The Seventh National Population Census	N/A The Seventh National Population Census	N/A The Seventh National Population Census	http://tjj.ah.gov.cn/oldfiles/tjj/tjjweb/tjnj/2021/cn.html	N/A The Seventh National Population Census
Data acquisition and creation	Census data				

Coping Capacity			
Theme Individual and	**Code** CC3	**Indicator** Percentage of households without individual means of transportation (%)	**Measuring unit/proxy indicator** Percentage of households without individual means of transportation: including passengers vehicles, cars etc (%)

Household					
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	Province	Province	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Coping Capacity					
Theme Individual and Household	**Code** CC4	**Indicator** Percentage of households without access to bank loans / (micro-) credits (%)		**Measuring unit/proxy indicator** Loans per capita (10000 yuan)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	

Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	Province	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Coping Capacity					
Theme Individual and Household	**Code** CC5	**Indicator** Percentage of population without a health insurance (%)		**Measuring unit/proxy indicator** Percentage of population without a health insurance (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	Province	Province	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition	Census data				

and creation	

Coping Capacity						
Theme Infrastructure and Services	**Code** CC_6	**Indicator** Access to emergency places			**Measuring unit/proxy indicator** Access to emergency places (density of hospitals per 10000 population)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion	
	-	-	-	-	-	
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.						
Delta	**Yangtze River Delta**				**Pearl River Delta**	
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**		
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province	
Year	2019	2019	2019	2019	2019	
Scale	Municipality	City	Province	City	City	
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/	
	Alternative source: http://www.openstreetmap.org					
Data acquisition and creation	Census data					

Coping Capacity					
Theme Infrastructure and Services	**Code** CC7	**Indicator** Percentage of households without access to water treatment (%)		**Measuring unit/proxy indicator** Percentage of households without access to water treatment (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Ministry of Housing and Urban-Rural Development of China				
Year	2020	2020	2020	2020	2020
Scale	Municipality	City	City	City	City
URL	N/A China Urban Construction Statistics Yearbook 2020				
Data acquisition and creation	Census data				

Coping Capacity					
Theme Infrastructure and Services	**Code** CC_8	**Indicator** Drainage system: Average length of drainage network per km^2		**Measuring unit/proxy indicator** Drainage system: Average length of drainage network per km^2	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	Not relevant	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Ministry of Housing and Urban-Rural Development of China				
Year	2020	2020	2020	2020	2020
Scale	Municipality	City	City	City	City
URL	N/A China Urban Construction Statistics Yearbook 2020				
Data acquisition and creation	Census data				

Coping Capacity					
Theme Infrastructure and Services	**Code** CC9	**Indicator** Density of transportation network		**Measuring unit/proxy indicator** Density of transportation network: roads (highways, primary / secondary / tertiary, local) (km/ km^2)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion

	-	-	-	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	GloBio				
Year	2018	2018	2018	2018	2018
Scale	Municipality	City	City	City	City
URL	www.globio.info				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Coping Capacity					
Theme Infrastructure and Services	**Code** CC10	**Indicator** Volume of water storage in a safe reservoir/container (m3)		**Measuring unit/proxy indicator** Volume of water storage in reservoirs (m^3 per capita)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China				
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Statistics Yearbook 2020				

Data acquisition and creation	Census data

Coping Capacity						
Theme Infrastructure and Services	**Code** CC11	**Indicator** Number of hospital beds per 1,000 inhabitants		**Measuring unit/proxy indicator** Number of hospital beds per 1,000 inhabitants		
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion	
	-	-	-	-	-	
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.						
Delta	**Yangtze River Delta**				**Pearl River Delta**	
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**		
Source	National Health Commission of China	Statistics Bureau of Jiangsu Province	National Health Commission of China	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province	
Year	2019	2020	2019	2019	2019	
Scale	Municipality	City	Province	City	City	
URL	N/A China Health Statistical Yearbook 2019	http://tj.jiangsu.gov.cn/col/col83749/index.html	N/A China Health Statistical Yearbook 2019	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/	
Data acquisition and creation	Census data					

Coping Capacity					
Theme Infrastructure and Services	**Code** CC12	**Indicator** Public health expenditure (% of GDP)		**Measuring unit/proxy indicator** Public health expenditure (% of GDP): including government health expenditure and social health expenditure	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	

Source	National Health Commission of China; National Bureau of Statistics of China				
Year	2018	2018	2018	2018	2018
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Health Statistical Yearbook 2019; China Statistical Yearbook 2019				
Data acquisition and creation	Census data				

Adaptive Capacity					
Theme Social Adaptation	**Code** AC1	**Indicator** Fixed assets per square kilometre		**Measuring unit/proxy indicator** Fixed assets investment (10,000 yuan/km^2)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2017	2017	2017	2017	2017
Scale	Municipality	Province	Province	Province	Province
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Adaptive Capacity			
Theme	**Code**	**Indicator**	**Measuring unit/proxy indicator**

Institutional Adaption	AC2	Existence of integrated development plans (yes/no)	Percentage of Disaster Prevention and Emergency Management Expenditure (%)		
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China				
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Statistical Yearbook 2020				
Data acquisition and creation	Census data				

Adaptive Capacity					
Theme Institutional Adaption	**Code** AC3	**Indicator** Percentage of GDP spent on research and development (%)		**Measuring unit/proxy indicator** Percentage of GDP spent on research and development (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China				
Year	2020	2020	2020	2020	2020
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Statistical Bulletin on Investment in R&D 2020				
Data acquisition and creation	Census data				

Ecosystem service

<table>
<tr><td colspan="6">Provisioning: Biomass</td></tr>
<tr><td>Theme
Agriculture</td><td>Code
ES_P1</td><td colspan="2">Indicator
Volumes of harvested production (ton year^{-1} per capita)</td><td colspan="2">Measuring unit/proxy indicator
Per capita annual output value of farming and animal husbandry (10000 yuan)</td></tr>
<tr><td rowspan="2">Hazard</td><td>Flooding</td><td>Cyclone</td><td>Storm Surge (Coastal flooding)</td><td>Drought</td><td>Salinity intrusion</td></tr>
<tr><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td colspan="6">Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.</td></tr>
<tr><td rowspan="2">Delta</td><td colspan="4">Yangtze River Delta</td><td rowspan="2">Pearl River Delta</td></tr>
<tr><td>Shanghai</td><td>Jiangsu</td><td>Zhejiang</td><td>Anhui</td></tr>
<tr><td>Source</td><td>National Bureau of Statistics of China</td><td>National Bureau of Statistics of China</td><td>National Bureau of Statistics of China</td><td>Statistics Bureau of Anhui Province</td><td>Statistics Bureau of Guangdong Province</td></tr>
<tr><td>Year</td><td>2019</td><td>2019</td><td>2019</td><td>2019</td><td>2019</td></tr>
<tr><td>Scale</td><td>Municipality</td><td>City</td><td>City</td><td>City</td><td>City</td></tr>
<tr><td>URL</td><td>http://www.stats.gov.cn/tjsj/ndsj/</td><td>http://www.stats.gov.cn/tjsj/ndsj/</td><td>http://www.stats.gov.cn/tjsj/ndsj/</td><td>http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html</td><td>http://stats.gd.gov.cn/gdtjnj/</td></tr>
<tr><td>Data acquisition and creation</td><td colspan="5">Census data</td></tr>
</table>

<table>
<tr><td colspan="6">Provisioning: Biomass</td></tr>
<tr><td>Theme
Aquaculture</td><td>Code
ES_P2</td><td colspan="2">Indicator
The amounts of aquaculture production (kg year^{-1}per capita)</td><td colspan="2">Measuring unit/proxy indicator
Per capita annual output value of fishery (10000 yuan)</td></tr>
<tr><td rowspan="2">Hazard</td><td>Flooding</td><td>Cyclone</td><td>Storm Surge (Coastal flooding)</td><td>Drought</td><td>Salinity intrusion</td></tr>
<tr><td>+</td><td>+</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td colspan="6">Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.</td></tr>
</table>

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://www.stats.gov.cn/tjsj/ndsj/	http://www.stats.gov.cn/tjsj/ndsj/	http://www.stats.gov.cn/tjsj/ndsj/	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Provisioning: Timber (energy/processing use)			
Theme Forestry	**Code** ES_P3	**Indicator** Volumes of forestry outputs (ton year^{-1} per capita)	**Measuring unit/proxy indicator** Per capita annual output value of forestry (10000 yuan)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://www.stats.gov.cn/tjsj/ndsj/	http://www.stats.gov.cn/tjsj/ndsj/	http://www.stats.gov.cn/tjsj/ndsj/	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition	Census data				

and creation	

Provisioning: Water					
Theme Water resource	**Code** ES_P4	**Indicator** Total groundwater recharge (mm/yr)		**Measuring unit/proxy indicator** Total groundwater recharge (mm/yr)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Müller Schmied et al., 2021)				
Year	1901-2016	1901-2016	1901-2016	1901-2016	1901-2016
Scale	Municipality	City	City	City	City
URL	https://doi.pangaea.de/10.1594/PANGAEA.918447?format=html#download				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Provisioning: Water					
Theme Water use	**Code** ES_P5	**Indicator** Total water abstraction for public use (m^3 per capita)		**Measuring unit/proxy indicator** Total water abstraction for household and service use (m^3 per capita)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Statistical Yearbook on Environment 2020				
Data acquisition and creation	Census data				

Provisioning: Water					
Theme Water use	**Code** ES_P6	**Indicator** Total water abstraction for agriculture and industry use (m^3 per capita)		**Measuring unit/proxy indicator** Total water abstraction for agriculture, industry and eco-environment use (m^3 per capita)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China	National Bureau of Statistics of China
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Statistical Yearbook on Environment 2020				
Data acquisition and creation	Census data				

Regulation & Maintenance: Soil quality regulation			
Theme Soil quality	**Code** ES_RM1	**Indicator** Total nitrogen (cg/kg)	**Measuring unit/proxy indicator** Total nitrogen (cg/kg)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	Not relevant	Not relevant	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	SoilGrids	SoilGrids	SoilGrids	SoilGrids	SoilGrids
Year	2020	2020	2020	2020	2020
Scale	Municipality	City	City	City	City
URL	https://soilgrids.org/				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Soil quality regulation					
Theme Soil quality	**Code** ES_RM2	**Indicator** Cation exchange capacity (cmol/kg)	**Measuring unit/proxy indicator** Cation exchange capacity (cmol/kg)		
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	Not relevant	Not relevant	Not relevant	Not relevant	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	SoilGrids	SoilGrids	SoilGrids	SoilGrids	SoilGrids
Year	2017	2017	2017	2017	2017
Scale	Municipality	City	City	City	City
URL	https://files.isric.org/soilgrids/former/2017-03-10/data/				

Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)

Regulation & Maintenance: Soil quality regulation					
Theme Soil quality	**Code** ES_RM3	**Indicator** Soil organic carbon stock (g/kg)	**Measuring unit/proxy indicator** Soil organic carbon stock (g/kg)		
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	Not relevant	Not relevant	Not relevant	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	SoilGrids	SoilGrids	SoilGrids	SoilGrids	SoilGrids
Year	2017	2017	2017	2017	2017
Scale	Municipality	City	City	City	City
URL	https://files.isric.org/soilgrids/former/2017-03-10/data/				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Erosion regulation			
Theme	**Code**	**Indicator**	**Measuring unit/proxy indicator**

Soil erosion	ES_RM4	Capacity of ecosystem to avoid soil erosion [index]		Total soil loss from soil erosion (ton ha^{-1} year^{-1})	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	Not relevant	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Joint Research Centre of the European Commission				
Year	2012	2012	2012	2012	2012
Scale	Municipality	City	City	City	City
URL	https://esdac.jrc.ec.europa.eu/content/global-soil-erosion				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Pollination					
Theme Pollination	**Code** ES_RM5	**Indicator** Pollination potential [index]		**Measuring unit/proxy indicator** Potential demand of crop production on bee pollination (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Pollination and crop production assessment (Chinese version)				
Year	2009	2009	2009	2009	2009
Scale	Municipality	Province	Province	Province	Province
URL	N/A				

	https://www.researchgate.net/publication/326265300_shoufenyuliangshishengchanpinggu/citations Alternative source: https://doi.org/10.5281/zenodo.5546600
Data acquisition and creation	Report data (Chinese)

Regulation & Maintenance: Biodiversity					
Theme Biodiversity	**Code** ES_RM6	**Indicator** Biodiversity Intactness Index		**Measuring unit/proxy indicator** Biodiversity Intactness Index	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Natural History Museum Data Portal				
Year	2016	2016	2016	2016	2016
Scale	Municipality	City	City	City	City
URL	data.nhm.ac.uk				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Biodiversity					
Theme Ecosystem & Habitat	**Code** ES_RM7	**Indicator** Mean Species Abundance (MSA)		**Measuring unit/proxy indicator** Mean Species Abundance (MSA)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Schipper et al., 2020)				
Year	2015	2015	2015	2015	2015
Scale	Municipality	City	City	City	City
URL	https://www.globio.info/globio-data-downloads				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Natural hazard protection					
Theme Hazard protection	**Code** ES_RM8	**Indicator** Percentage of windbreaks (%)		**Measuring unit/proxy indicator** Green space rate of built district (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Ministry of Housing and Urban-Rural Development of the People’s Republic of China				
Year	2020	2020	2020	2020	2020
Scale	Municipality	City	City	City	City
URL	https://www.mohurd.gov.cn/gongkai/fdzdgknr/sjfb/index.html				
Data acquisition and creation	Census data				

Regulation & Maintenance: Air quality regulation			
Theme Air quality	Code ES_RM9	**Indicator** Air quality index	**Measuring unit/proxy indicator** World Air Quality Index (WAQI)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	Not relevant	Not relevant	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	WAQI project				
Year	2014-2020	2014-2020	2014-2020	2014-2020	2014-2020
Scale	Municipality	City	City	City	City
URL	https://aqicn.org/data-platform/register/				

Regulation & Maintenance: Climate regulation					
Theme Forest carbon	**Code** ES_RM10	**Indicator** Forest carbon potential (%)		**Measuring unit/proxy indicator** Net ecosystem exchange	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	Not relevant	Not relevant	Not relevant	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	NASA Earth Data				
Year	1950-2010	1950-2010	1950-2010	1950-2010	1950-2010
Scale	Municipality	City	City	City	City
URL	https://doi.org/10.3334/ORNLDAAC/1296				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Water regulation

Theme Water retention	**Code** ES_RM11	**Indicator** Water retention index		**Measuring unit/proxy indicator** Field Capacity based on Water Retention Model	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	Not relevant	Not relevant	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Zhang et al., 2018)				
Year	2018	2018	2018	2018	2018
Scale	Municipality	City	City	City	City
URL	http://www.u.arizona.edu/~ygzhang/download.html				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Regulation & Maintenance: Water regulation					
Theme Water quality	**Code** ES_RM12	**Indicator** Water quality		**Measuring unit/proxy indicator** Water scarcity including water quantity and quality	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(van Vliet et al., 2021)				
Year	1979-2010				

Scale	Municipality	City	City	City	City
URL	https://doi.org/10.1088/1748-9326/abbfc3 (personal request)				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Cultural					
Theme Tourism	**Code** ES_C1	**Indicator** Percentage of tourism to GDP (%)		**Measuring unit/proxy indicator** Percentage of tourism to GDP (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	Province	Province	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Cultural					
Theme Recreation	**Code** ES_C3	**Indicator** Surface area of sites of community importance (ha)		**Measuring unit/proxy indicator** Public recreational park green space (m^2 per capita)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Ministry of Housing and Urban-Rural Development of the People’s Republic of China				
Year	2020	2020	2020	2020	2020
Scale	Municipality	City	City	City	City
URL	https://www.mohurd.gov.cn/gongkai/fdzdgknr/sjfb/index.html				
Data acquisition and creation	Census data				

Cultural					
Theme Aesthetic	**Code** ES_C2	**Indicator** Employment in tourism and other aesthetic activities (%)		**Measuring unit/proxy indicator** Employment of tourism in A level scenic spot (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Ministry of Culture and Tourism of China				
Year	2019	2019	2019	2019	2019
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Culture, Cultural Relics and Tourism Statistical Yearbook 2020				
Data acquisition and creation	Census data				

Ecosystem Vulnerability

Ecosystem Susceptibility					
Theme Habitat Destruction	**Code** ES1	**Indicator** Percentage of deforested area (%)		**Measuring unit/proxy indicator** Percentage of deforested area (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	+	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Hansen et al., 2013)				
Year	2000-2014	2000-2014	2000-2014	2000-2014	2000-2014
Scale	Municipality	City	City	City	City
URL	http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.2.html				
Data acquisition and creation	Tool: ArcMap 10.8 1. Create a file Geodatabase a. Right click on database –> new –> mosaic dataset b. Add raster to mosaic 2. Reclassify: a. 0%: 0 (no forest) b. 1% - 100%: 1 (forest) 3. Clip Raster with delta boundary 4. Project rasters (gain and loss) to UTM51N 5. Use minus (Spatial Analysis tool) to subtract loss layer minus gain layer 6. Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL				

	g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)

Ecosystem Susceptibility					
Theme Habitat Destruction	**Code** ES2	**Indicator** Percentage of wetland loss (%)		**Measuring unit/proxy indicator** Percentage of wetland loss (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	+	Not relevant	+	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	GlobeLand30				
Year	2000-2020	2000-2020	2000-2020	2000-2020	2000-2020
Scale	Municipality	City	City	City	City
URL	http://www.globallandcover.com/home_en.html				
Data acquisition and creation	Tool: ArcMap 10.8 1. Create a file Geodatabase a. Right click on database –> new –> mosaic dataset b. Add raster to mosaic 2. Reclassify: a. other land cover: 0 b.wetland:1 3. Clip Raster with delta boundary 4. Project rasters (gain and loss) to UTM51N 5. Use minus (Spatial Analysis tool) to subtract loss layer minus gain layer 6. Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Ecosystem Susceptibility					
Theme Habitat Destruction	**Code** ES3	**Indicator** Percentage of area covered by "problem soils" (%)		**Measuring unit/proxy indicator** Percentage of sandy/desertificated area in arable land (%)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	Not relevant	Not relevant	Not relevant	+	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China				
Year	2014	2014	2014	2014	2014
Scale	Municipality	Province	Province	Province	Province
URL	N/A China Statistical Yearbook on Environment 2020				
Data acquisition and creation	Census data				

Ecosystem Susceptibility					
Theme Habitat Degradation	**Code** ES4	**Indicator** Increased use of chemicals and fertilisers (qualitative/ quantitative)		**Measuring unit/proxy indicator** Increased use of pesticides and fertilizers in 2008 and 2019 (tons/ha)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	Not relevant	Not relevant	Not relevant	Not relevant	+
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	National Bureau of Statistics of China	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	National Bureau of Statistics of China
Year	2008, 2019	2008, 2019	2008, 2019	2008, 2019	2008, 2019
Scale	Municipality	Province	Province	Province	Province

URL	http://www.stats.gov.cn/tjsj/ndsj/	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://www.stats.gov.cn/tjsj/ndsj/
Data acquisition and creation	Census data				

Ecosystem Susceptibility					
Theme Habitat Degradation	**Code** ES5	**Indicator** Normalized Difference Vegetation Index (NDVI)		**Measuring unit/proxy indicator** Normalized Difference Vegetation Index (NDVI)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Xinliang, 2019)				
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	http://www.resdc.cn/DOI				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Ecosystem Susceptibility					
Theme Habitat Fragmentation	**Code** ES6	**Indicator** Forest connectivity		**Measuring unit/proxy indicator** Probability of forest connectivity [index]	
Hazard	Flooding	Cyclone	Storm Surge	Drought	Salinity intrusion

			(Coastal flooding)		
	-	-	-	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Hansen et al., 2013); (Saura and Torné, 2009)				
Year	2014	2014	2014	2014	2014
Scale	Municipality	City	City	City	City
URL	http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.2.html; http://www.conefor.org/index.html				
Data acquisition and creation	Tool: ArcMap 10.8 Calculation processes are based on the Supplementary Material from Anderson et al. (2021) 1. Create a file Geodatabase a. Right click on database –> new –> mosaic dataset b. Add raster to mosaic 2. Reclassify: a. 0%: 0 (no forest) b. 1% - 100%: 1 (forest) 3. Clip Raster with delta boundary 4. Project rasters (gain and loss) to UTM51N 5. Use plus to add the forest gain to the forest cover layer 6. Reclassify: a. 0%: 0 (no forest) b. 1 - 2: 1 (forest) 7. Use minus to subtract loss layer from layer created under step 5 8. Reclassify: a. -1 - 0%: 0 (no forest) b. 1: 1 (forest) 9. Raster to polygon (Conversion tool) 10. Delete polygons that are smaller than 5ha 11. Intersect layer with admin boundary 12. Add field (short integer) called nodeID to Attribute table: Field calculator: 1 + FID 13. Export forest polygons for each district 14. Conefor GIS extension (Saura and Torné, 2009)				

	15. Calculate node files: a. Restricted analysis to features within specified distance: 1000 m b. Calculate from Feature Edges c. Click all output options 16. Input corresponding output node file and distance file and use the following settings: 1000m; connection (partial); probabilistic index PC; 0,01 probability of occurrence

Ecosystem Susceptibility					
Theme Habitat Fragmentation	**Code** ES7	**Indicator** Wetland connectivity		**Measuring unit/proxy indicator** Probability of wetland connectivity [index]	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	(Gumbricht et al., 2017); (Saura and Torné, 2009)				
Year	2017	2017	2017	2017	2017
Scale	Municipality	City	City	City	City
URL	https://data.cifor.org/dataset.xhtml?persistentId=doi:10.17528/CIFOR/DATA.00058; http://www.conefor.org/index.html				
Data acquisition and creation	Tool: ArcMap 10.8 The raster processing process is the same as for the indicator ‘% of wetland loss’. The calculation process is the same as Forest Connectivity.				

Ecosystem Susceptibility					
Theme Habitat Fragmentation	**Code** ES8	**Indicator** River connectivity		**Measuring unit/proxy indicator** Connectivity status index (CSI)	
Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	Not relevant
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					
Delta	**Yangtze River Delta**				**Pearl River Delta**

	Shanghai	Jiangsu	Zhejiang	Anhui	
Source	(Grill et al., 2019)				
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	City	City	City
URL	https://doi.org/10.6084/m9.figshare.7688801				
Data acquisition and creation	Tool: Arcmap 10.8 Zonal Statistics as Table a. Input raster or feature zone data: census tracts shapefile b. Zone field: AFFGEOID c. Input value raster: clipped data set (raster) d. Output table: a folder location for data storage e. Ignore NoData in calculations (optional) f. Statistics type (optional): ALL g. Join census tracts layer with zonal statistic table outcome (tool: Excel VLOOKUP)				

Ecosystem Robustness			
Theme Ecosystem Conservation	**Code** ER1	**Indicator** Percentage of government expenditure on environmental protection (%)	**Measuring unit/proxy indicator** Percentage of government expenditure on environmental protection (%)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-
Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.					

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Shanghai Statistics Bureau	Statistics Bureau of Jiangsu Province	Statistics Bureau of Zhejiang Province	Statistics Bureau of Anhui Province	Statistics Bureau of Guangdong Province
Year	2019	2019	2019	2019	2019
Scale	Municipality	City	Province	City	City
URL	http://tjj.sh.gov.cn/tjnj/index.html	http://tj.jiangsu.gov.cn/col/col83749/index.html	https://tjj.zj.gov.cn/col/col1525563/index.html	http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html	http://stats.gd.gov.cn/gdtjnj/
Data acquisition and creation	Census data				

Ecosystem Robustness

Theme	**Code**	**Indicator**	**Measuring unit/proxy indicator**
Ecosystem restoration	ER2	Percentage of area for nature reserves (%)	Percentage of area for nature reserves (%)

Hazard	Flooding	Cyclone	Storm Surge (Coastal flooding)	Drought	Salinity intrusion
	-	-	-	-	-

Increasing [+] or decreasing [-] represents the relationship between high indicator values and vulnerability and risk.

Delta	**Yangtze River Delta**				**Pearl River Delta**
	Shanghai	**Jiangsu**	**Zhejiang**	**Anhui**	
Source	Ministry of Ecology and Environment of the People's Republic of China				
Year	2011	2012	2012	2012	2011
Scale	Municipality	City	City	City	City
URL	https://www.mee.gov.cn/ywgz/zrstbh/zrbhdjg/201208/t20120824_235190.shtml	https://www.mee.gov.cn/ywgz/zrstbh/zrbhdjg/201309/t20130927_260959.shtml	https://www.mee.gov.cn/ywgz/zrstbh/zrbhdjg/201309/t20130927_260958.shtml	https://www.mee.gov.cn/ywgz/zrstbh/zrbhdjg/201309/t20130927_260957.shtml	https://www.mee.gov.cn/ywgz/zrstbh/zrbhdjg/201208/t20120824_235180.shtml

Data acquisition and creation	Census data

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Appendix 8 Data processing (Chapter 3)

1. Expert consultation details

1.1 Criteria and method for defining and recruiting experts

Experts were selected based on their knowledge and experience in related disciplines, with required academic or governmental backgrounds. They were approached through professional networks, direct invitations based on their published works or contributions to relevant fields, and their combinations (snowball sampling process).

1.2 Backgrounds of the experts

The experts consulted came from various academic institutions and government sectors. Given the interdisciplinary nature of this study, a diverse group of experts were involved to gather wider perspectives.

1.3 List of received expert questionnaires (a total of 42 participants)

Background	Number of participants	Affiliation Type
Agriculture	1	Government sector
	1	University
	2	Research center
Land Management	1	State-owned enterprise
	1	Research center
Ecosystem Service	4	University
	2	Research center
Risk Management	3	University
Environmental Assessment	2	Research center
	1	University
Urban Sustainability	1	Private company
	1	Research center
Ecosystem Conservation & Restoration	2	University
Ecology (Urban, Soil, Ecological Planning, etc.)	3	Research center
	1	University
Climate Change Adaption	2	University
Water	3	Research center
	1	Government sector
Environmental Management	1	State-owned enterprise
	1	University
	8	Research center

1.4 Rationale behind the questions

Expert consultations involved questionnaires designed to identify relevant indicators and their weights in the study areas. Questions were formulated based on the literature review, and aimed to gain more local or professional knowledge on the applicability of these indicators to the study areas, the relative importance of indicators, and their directional effects on vulnerability.

1.5 Potential biases and strategies employed to minimise these biases

Potential biases from expert consultation included subjective judgments, differences in expertise, and unfamiliarity with the risk assessment field. Additionally, there is the possibility that the dominant opinions determine the results. To mitigate these biases, AHP and IAHP methods were used to systematically quantify expert judgments. Consistency ratios (CR) were calculated to ensure the reliability of the pairwise comparisons ($CR < 0.1$). Sensitivity analysis evaluates how different inputs impact the final results. Due to a lack of direct damage data, this study compared risk profiles generated using expert weights with those using equal weights to ensure the results were not determined by a single set of weights.

2. Missing value analysis

The mean of the surrounding areas is used to represent the missing values: Total groundwater recharge, Total nitrogen, Air quality and Water quality.

3. Outlier analysis (Box plots: data point outside the whiskers of the 1.5 inter-quartile range)

Following the results of box plots, the raw data of outliers were checked. Identified outliers were changed to the 5%/95% scores (winsorization approach): Total groundwater recharge, Capacity of ecosystem to avoid soil erosion, Net ecosystem exchange, Water quality, Percentage of deforested area, Percentage of wetland loss, Proportion of area covered by lacustrine algal boom, Wetland connectivity, Mean Species Abundance (MSA)

4. Multicollinearity analysis (Correlation Coefficient: Kendall's tau_b)

4.1 Social susceptibility

Indicator ‘Percentage of population without access to (improved) sanitation (%)’ was excluded due to $r > 0.90$ at the 0.01 level with the indicator ‘Percentage of families below the poverty line in total households (%)’.

Indicator ‘Percentage of the population with disabilities (%)’ was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Percentage of population without access to clean water (%)’.

4.2 Lack of coping and adaptive capacity

Indicator ‘Percentage of households without gross savings (%) was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Percentage of households without access to bank loans / (micro-) credits (%)’ and indicator ‘Number of hospital beds per 1,000 inhabitants’.

Indicator ‘Access to shelter places’ was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Existence of integrated development plans (yes/no)’.

Indicator ‘Foreign Direct Investment (% of GDP)’ and indicator ‘Private health expenditure (% of GDP) were excluded due to r > 0.90 at the 0.01 level with the indicator ‘Public health expenditure (% of GDP)’.

4.3 Ecosystem service

No multicollinearity issue was observed.

4.4 Ecosystem susceptibility

No multicollinearity issue was observed.

4.5 Ecosystem robustness

No multicollinearity issue was observed.

5. Reliability index for the PRD and YRD

	PRD		YRD	
	Number of indicators	Reliability Score (%)	Number of indicators	Reliability Score (%)
Percentage of missing data and outliers for vulnerability	8/1539	99.48	15/1539	99.03
Percentage of missing hazard data	3/45	93.33	6/135	95.56

Percentage of proxy indicators	18/57	68.42	18/57	68.42
Percentage of indicator data at provincial level	153/513	70.18	533/1539	65.37
		83		**82**

Appendix 9 Supplementary material of Chapter 4

Appendix 9 provides detailed information about 1) Study area; 2) Indicator list and data sources; 3) Methods: frameworks and the formulas; and 4) Data processing results.

1) Study Area

PRD:

Guangzhou; Foshan; Zhaoqing; Shenzhen; Dongguan; Huizhou; Zhuhai; Zhongshan; Jiangmen

YRD:

Shanghai; Jiangsu province (Nanjing; Wuxi; Changzhou; Suzhou; Nantong; Yangzhou; Zhenjiang; Yancheng; Taizhou_J); Zhejiang province (Hangzhou; Ningbo; Wenzhou; Huzhou; Jiaxing; Shaoxing; Jinhua; Zhoushan; Taizhou); Anhui province (Hefei; Wuhu; Ma'anshan; Tongling; Anqing; Chuzhou; Chizhou; Xuancheng)

2) Indicator list and data sources

The table primarily presents data sources. For details regarding the data processing steps, please refer to Appendix 6.

Indicator types	Applicable framework	Indicator name	Data sources
Hazard	DELTA-ES-SES	Drought: Standardized precipitation evapotranspiration index (SPEI)	EAR5 dataset (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5); (Vicente-Serrano et al., 2010)
		Flooding: Mean water depth (in m)	European Commission, Joint Research Centre: https://ec.europa.eu/jrc/en/research-topic/floods
		Storm surge: Sea levels (in m)	(Muis et al., 2016): https://www.geonode-gfdrrlab.org/
		Cyclone: Wind speed (km/h); Cyclone frequency	UNEP/DEWA/GRID-Europe: Hazard: http://preview.grid.unep.ch
		Salinity intrusion: Salinity (TDS concentrations) (mg/l)	(van Vliet et al., 2021): https://doi.org/10.1088/1748-9326/abbfc3 (personal request)
Exposure	DELTA-ES-SES; GDRI	Percentage of population exposed to multiple hazards (%); Percentage of economics exposed to multiple hazards (%); Ecosystem exposed to multiple hazards (%)	Population: https://www.worldpop.org/ Economics: http://www.resdc.cn/DOI Land cover: http://www.globallandcover.com/home_en.html
Social Susceptibility	DELTA-ES-SES; GDRI	% of population without access to clean water	http://tjj.sh.gov.cn/tjnj/index.html;
		Travel time to closest city	

		Proxy: Percentage of rural population (%)	http://tj.jiangsu.gov.cn/col/col83749/index.html; https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		% female-headed households Proxy: Percentage female population (%)	
		% of contribution of primary industry to GDP	
		% malnourished population Proxy: Percentage underweight children under the age of five (%)	China Health Statistical Yearbook 2019
		% of illiterate population	
		Dependency ratio	http://www.stats.gov.cn/tjsj/ndsj/; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		% of families below the poverty line in total households	Poverty Monitoring Report of Rural China 2019
		% of households without access to irrigation	https://www.fao.org/aquastat/en/
Coping & Adaptative Capacity	DELTA-ES-SES; GDRI	The average years of education (year)	The Seventh National Population Census, China
		% of households without individual means of transportation Proxy: Percentage of households without individual means of transportation: including passengers vehicles, cars etc (%)	http://tjj.sh.gov.cn/tjnj/index.html; http://tj.jiangsu.gov.cn/col/col83749/index.html; https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		% of households without access to bank loans / (micro-) credits Proxy: Loans per capita (10000 yuan)	
		% of population without a health insurance	
		Access to emergency places Proxy: Density of hospitals per 10000 population)	
		% of households without access to water treatment	China Urban Construction Statistics Yearbook 2020
		Drainage system: Average length of Drainage network	
		Density of transportation network: roads (highways, primary / secondary / tertiary, local) (km/ km^2)	www.globio.info
		Volume of water storage in a safe reservoir/container	China Statistics Yearbook 2020
		Number of hospital beds per 1,000 inhabitants	China Health Statistical Yearbook 2019; http://tj.jiangsu.gov.cn/col/col83749/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		Public health expenditure (% of GDP): including government health expenditure and social health expenditure	China Health Statistical Yearbook 2019; China Statistical Yearbook 2019

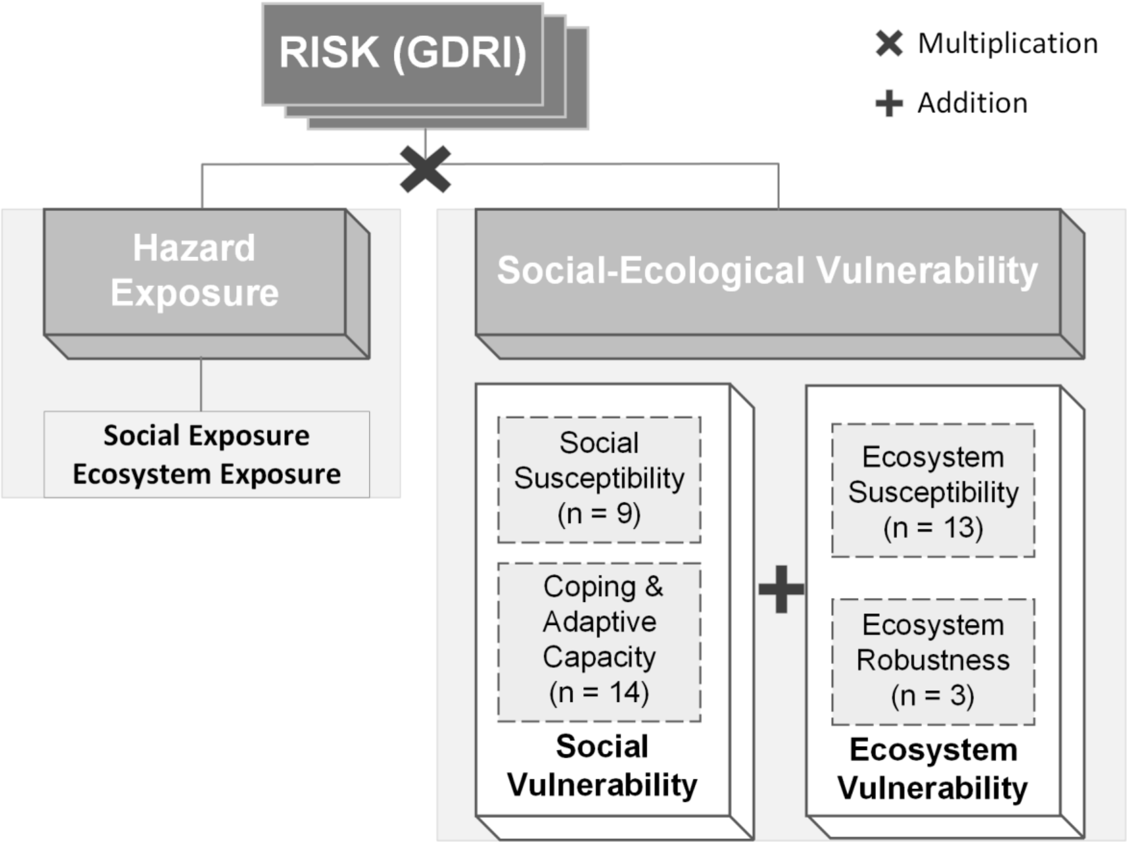
		Fixed assets per square kilometre: Fixed assets investment (10,000 yuan/km^2)	http://tjj.sh.gov.cn/tjnj/index.html; http://tj.jiangsu.gov.cn/col/col83749/index.html; https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		Existence of integrated development plans (yes/no) Proxy: Percentage of Disaster Prevention and Emergency Management Expenditure (%)	China Statistical Yearbook 2020
		% of GDP spent on research and development	China Statistical Bulletin on Investment in R&D 2020
Ecosystem Susceptibility	DELTA-ES-SES; GDRI	% of deforested area	http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.2.html
		% of wetland loss	http://www.globallandcover.com/home_en.html
		% of area covered by "problem soils" Proxy: Percentage of sandy/desertificated area in arable land (%)	China Statistical Yearbook on Environment 2020
		Increased use of chemicals and fertilisers in 2008 and 2019 (tons/ha)	http://tjj.sh.gov.cn/tjnj/index.html; http://tj.jiangsu.gov.cn/col/col83749/index.html; https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html
		Normalized Difference Vegetation Index (NDVI)	http://www.resdc.cn/DOI
		Forest connectivity	http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.2.html; http://www.conefor.org/index.html
		Wetland connectivity	https://data.cifor.org/dataset.xhtml?persistentId=doi:10.17528/CIFOR/DATA.00058; http://www.conefor.org/index.html
		River connectivity	(Grill et al., 2019)
	GDRI	Total groundwater recharge	(Müller Schmied et al., 2021)
		Soil organic carbon stock	https://files.isric.org/soilgrids/former/2017-03-10/data/
		Cation exchange capacity	
		Biodiversity Intactness Index	data.nhm.ac.uk
		Water quality index	(van Vliet et al., 2021): https://doi.org/10.1088/1748-9326/abbfc3 (personal request)
Ecosystem Robustness	DELTA-ES-SES; GDRI	% of government expenditure on environmental protection	http://tjj.sh.gov.cn/tjnj/index.html; http://tj.jiangsu.gov.cn/col/col83749/index.html;

			https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		% of area for nature reserves	Ministry of Ecology and Environment of the People's Republic of China
	GDRI	Mean Species Abundance (MSA)	https://www.globio.info/globio-data-downloads
Provisioning	DELTA-ES-SES	Volumes of harvested production Proxy: Per capita annual output value of farming and animal husbandry (10000 yuan)	http://tjj.sh.gov.cn/tjnj/index.html; http://tj.jiangsu.gov.cn/col/col83749/index.html; https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		The amounts of aquaculture production Proxy: Per capita annual output value of fishery (10000 yuan)	
		Volumes of forestry outputs Proxy: Per capita annual output value of forestry (10000 yuan)	
		Total groundwater recharge	https://doi.pangaea.de/10.1594/PANGAEA.918447?format=html#download
		Total water abstraction for public use	China Statistical Yearbook on Environment 2020
		Total water abstraction for agriculture and industry use	
Regulation & Maintenance		Total nitrogen	https://soilgrids.org/
		Soil organic carbon stock	https://files.isric.org/soilgrids/former/2017-03-10/data/
		Cation exchange capacity	
		Capacity of ecosystem to avoid soil erosion Proxy: Total soil loss from soil erosion (ton ha-1 year-1)	https://esdac.jrc.ec.europa.eu/content/global-soil-erosion
		Pollination potential [index] Proxy: Potential demand of crop production on bee pollination (%)	https://www.researchgate.net/publication/326265300_shoufenyuliangshishengchanpinggu/citations (Chinese) Alternative source: https://doi.org/10.5281/zenodo.5546600
		Biodiversity Intactness Index	data.nhm.ac.uk
		Mean Species Abundance (MSA)	https://www.globio.info/globio-data-downloads
		% of windbreaks Proxy: Green space rate of built district (%)	https://www.mohurd.gov.cn/gongkai/fdzdgknr/sjfb/index.html
		Air quality index	https://aqicn.org/data-platform/register/
		Net ecosystem exchange	https://doi.org/10.3334/ORNLDAAC/1296
		Water retention index	http://www.u.arizona.edu/~ygzhang/download.html
		Water quality index Proxy: Water scarcity including water quantity and quality	(van Vliet et al., 2021): https://doi.org/10.1088/1748-9326/abbfc3 (personal request)
Cultural		% of tourism to GDP	http://tjj.sh.gov.cn/tjnj/index.html;

			http://tj.jiangsu.gov.cn/col/col83749/index.html; https://tjj.zj.gov.cn/col/col1525563/index.html; http://tjj.ah.gov.cn/ssah/qwfbjd/tjnj/index.html; http://stats.gd.gov.cn/gdtjnj/
		Surface area of sites of community importance Proxy: Public recreational park green space (m2 per capita)	https://www.mohurd.gov.cn/gongkai/fdzdgknr/sjfb/index.html
		Employment in tourism and other aesthetic activities (%) Proxy: Employment of tourism in A level scenic spot (%)	China Culture, Cultural Relics and Tourism Statistical Yearbook 2020

3) Methods

GDRI (Figure A.1):



$$RISK_{SES} = HAZEXP_{SES} * VUL_{SES} \qquad Eq.\ (A.1)$$

Where $HAZEXP_{SES}$ is the (hazard) exposure score, which is calculated as

$$HAZEXP_{SES} = \sum_{i=1}^{n}(w_i * EC_{SES}) \qquad Eq.\ (A.2)$$

Here EC_{SES} is the different exposure component of SES where w_i is the weight of each type of exposure indicator. Besides, VUL_{SES} is the vulnerability score of SES, which use the mean of two vulnerability domains (after combining the weights w_j), which is calculated using

$$VUL_{SES} = \sum_{j=1}^{n}(w_j * VD_{SES}) \qquad Eq.\ (A.3)$$

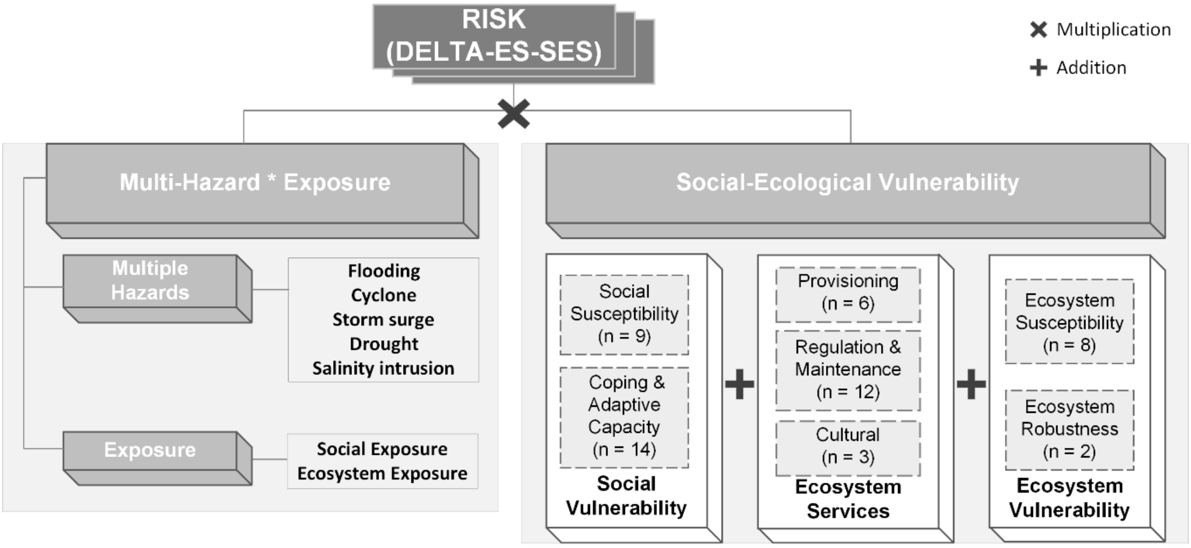
VD_{SES} refers to ecosystem vulnerability and social vulnerability, which is calculated using

$$VD_{SES} = \sum_{s=1}^{n}(w_s * VD_s) \qquad Eq.\ (A.4)$$

where w_s is the weights of indicators in the sub-component of vulnerability domain (VD) (e.g. indicators of ecosystem susceptibility and robustness). Here VD is calculated by the aggregation of each normalized indicator (x_k') with eueal weights (w_k).

$$VD = \sum_{k=1}^{n}(w_k * x'_k) \qquad Eq.\ (A.5)$$

DELTA-ES-SES (Figure A.2):



$$RISK_{SES} = HAZ_{SES} * EXP_{SES} * VUL_{SES} \qquad Eq.\ (A.6)$$

Where HAZ_{SES} is the hazard score; EXP_{SES} is the exposure score, which is calculated as

$$EXP_{SES} = \sum_{i=1}^{n}(w_i * EC_{SES}) \qquad Eq.\ (A.7)$$

Here EC_{SES} is the different exposure component of SES where w_i is the weight of each type of exposure indicator. Besides, VUL_{SES} is the vulnerability score of SES, which use the mean of three vulnerability domains (after combining the weights w_j), which is calculated using

$$VUL_{SES} = \sum_{j=1}^{n}(w_j * VD_{SES}) \qquad Eq.\ (A.8)$$

VD_{SES} refers to ecosystem vulnerability, ecosystem services, and social vulnerability, which is calculated using

$$VD_{SES} = \sum_{s=1}^{n}(w_s * VD_s) \qquad Eq.\ (A.9)$$

where w_s is the weights of indicators in the sub-component of vulnerability domain (VD) (e.g. indicators of ecosystem susceptibility and robustness). Here VD is calculated by the aggregation of each normalized indicator (x_k') with specific weights (w_k).

$$VD = \sum_{k=1}^{n}(w_k * x'_k) \qquad Eq.\ (A.10)$$

4) Data Processing

The data processing workflow followed missing value analysis, outlier processing (winsorization treatment), multicollinearity checks, and rescaling (min-max normalization).

4.1 Missing value analysis

The mean of the surrounding areas is used to represent the missing values: Total groundwater recharge, Total nitrogen, Air quality and Water quality.

4.2 Outlier analysis (Box plots: data point outside the whiskers of the 1.5 inter-quartile range)

Following the results of box plots, the raw data of outliers were checked. Identified outliers were changed to the 5%/95% scores (winsorization approach): Total groundwater recharge, Capacity of ecosystem to avoid soil erosion, Net ecosystem exchange, Water quality, Percentage of deforested area, Percentage of wetland loss, Proportion of area covered by lacustrine algal boom, Wetland connectivity, Mean Species Abundance (MSA)

4.3 Multicollinearity analysis (Correlation Coefficient: Kendall's tau_b)

i. Social susceptibility

Indicator ‘Percentage of population without access to (improved) sanitation (%)’ was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Percentage of families below the poverty line in total households (%)’.

Indicator ‘Percentage of the population with disabilities (%)’ was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Percentage of population without access to clean water (%)’.

ii. Lack of coping and adaptive capacity

Indicator ‘Percentage of households without gross savings (%) was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Percentage of households without access to bank loans / (micro-) credits (%)’ and indicator ‘Number of hospital beds per 1,000 inhabitants’.

Indicator ‘Access to shelter places’ was excluded due to r > 0.90 at the 0.01 level with the indicator ‘Existence of integrated development plans (yes/no)’.

Indicator ‘Foreign Direct Investment (% of GDP)’ and indicator ‘Private health expenditure (% of GDP) were excluded due to r > 0.90 at the 0.01 level with the indicator ‘Public health expenditure (% of GDP)’.

iii. No multicollinearity issue was observed in Ecosystem service, Ecosystem susceptibility, and Ecosystem robustness

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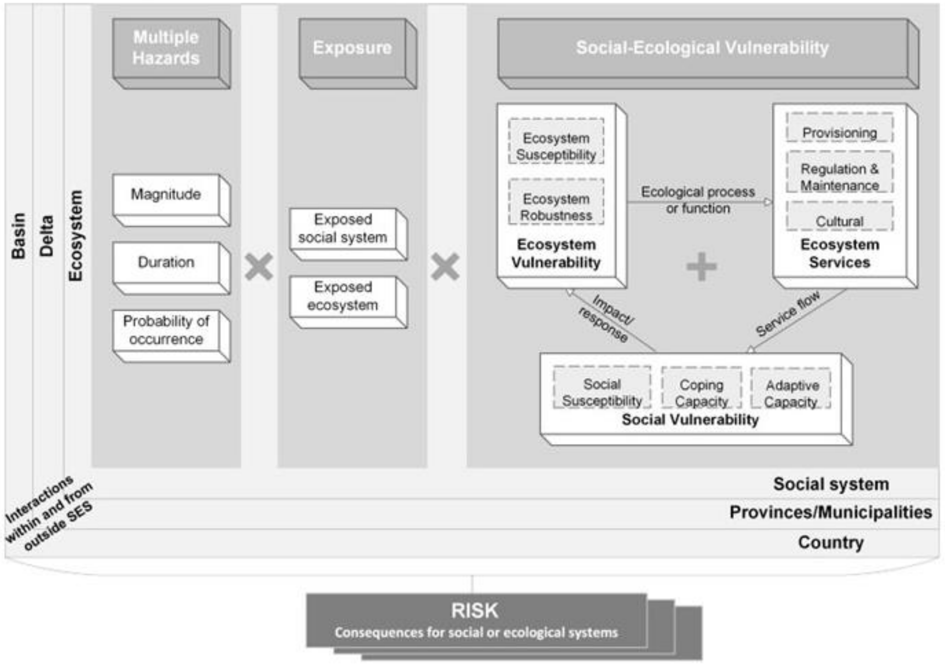
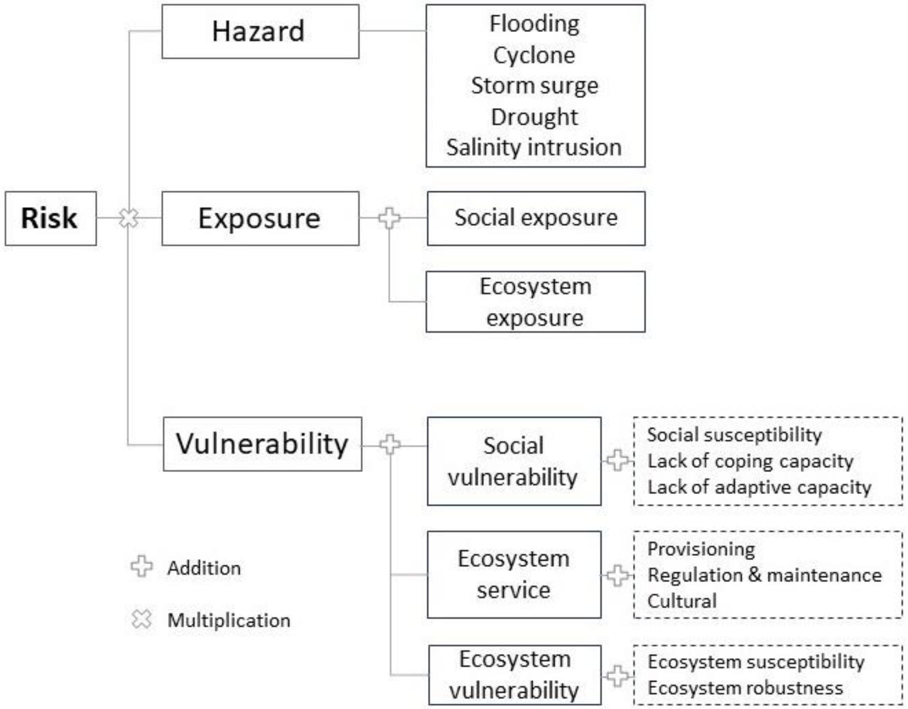
Appendix 10 Additional material: conceptual framework and risk index structure

- Conceptual framework & risk components in Chapter 2



- Aggregative modular structure of risk index in Chapter 3 and 4



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