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# Profiling resilience and adaptation in mega deltas: A comparative assessment of the Mekong, Yellow, Yangtze, and Rhine deltas

Claudia Kuenzer[a,b], Valentin Heimhuber[c,*], John Day[d], Olli Varis[e], Tom Bucx[f], Fabrice Renaud[g], Liu Gaohuan[h], Vo Quoc Tuan[i], Thorsten Schlurmann[j], William Glamore[c]

[a] German Remote Sensing Data Center (DFD), German Aerospace Center (DLR), Muenchener Strasse 20, D-82234, Wessling, Germany
[b] Institute for Geography and Geology, University of Wuerzburg, D-97074, Wurzburg, Germany
[c] Water Research Laboratory, School of Civil & Environmental Engineering, UNSW Sydney, NSW, 2052, Australia
[d] Louisiana State University, Oceanography and Coastal Sciences, Baton Rouge, LA, USA
[e] Aalto University, Department of Built Environment, Aalto, Finland
[f] Deltares, Water Resources and Delta Management, Delft, the Netherlands
[g] University of Glasgow, School of Interdisciplinary Studies, Glasgow, United Kingdom
[h] Institute of Geographic Science and Natural Resources Research (IGSNRR), Beijing, China
[i] Can Tho University, College of the Environment, Can Tho, Viet Nam
[j] University of Hannover, Franzius Institute, Hannover, Germany

A R T I C L E I N F O

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Risk assessment

A B S T R A C T

River deltas and estuaries are disproportionally-significant coastal landforms that are inhabited by nearly 600 M people globally. In recent history, rapid socio-economic development has dramatically changed many of the World's mega deltas, which have typically undergone agricultural intensification and expansion, land-use change, urbanization, water resources engineering and exploitation of natural resources. As a result, mega deltas have evolved into complex and potentially vulnerable socio-ecological systems with unique threats and coping capabilities. The goal of this research was to establish a holistic understanding of threats, resilience, and adaptation for four mega deltas of variable geography and levels of socio-economic development, namely the Mekong, Yellow River, Yangtze, and Rhine deltas. Compiling this kind of information is critical for managing and developing these complex coastal areas sustainably but is typically hindered by a lack of consistent quantitative data across the ecological, social and economic sectors. To overcome this limitation, we adopted a qualitative approach, where delta characteristics across all sectors were assessed through systematic expert surveys. This approach enabled us to generate a comparative assessment of threats, resilience, and resilience-strengthening adaptation across the four deltas. Our assessment provides novel insights into the various components that dominate the overall risk situation in each delta and, for the first time, illustrates how each of these components differ across the four mega deltas. As such, our findings can guide a more detailed, sector specific, risk assessment or assist in better targeting the implementation of risk mitigation and adaptation strategies.

## 1. Introduction and scope of this paper

Coastal river deltas and estuaries are among the most densely populated places on earth (Kuenzer and Renaud, 2012). The locational advantages of river deltas and estuaries generate a wide variety of assets. Deltas typically have a flat topography, which facilitates human settlement, agriculture and economic development (Davidson-Arnott, 2010). They provide access to salt and fresh water, fluvial and marine resources, ample opportunities for ice-free harbours, and transport connections into the hinterland of a river basin (Kuenzer et al., 2014b, 2014a). Deltas are often home to underground reserves of oil and gas, and/or salts (Davidson-Arnott, 2010; Ottinger et al., 2013). Above ground, deltas are usually highly fragmented environments, providing different marine, brackish, and terrestrial ecosystems. Therefore, a rich and complex wetland flora and fauna is found in these environments, and numerous deltas worldwide are important resting and breeding grounds for migratory birds (Aung et al., 2013; Cui et al., 2009; Kuenzer et al., 2014b).

* Corresponding author.
*E-mail addresses:* Claudia.Kuenzer@dlr.de (C. Kuenzer), v.heimhuber@unsw.edu.au (V. Heimhuber).

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Due to these locational advantages, in many countries, river deltas provide the major national contribution to agricultural and industrial production (Kuenzer and Renaud, 2012). From the oil rich and densely settled Mississippi Delta area and its hinterland in the USA, to the bustling Pearl or Yangtze River Delta (YaRD) in China, the agriculturally highly productive Nile Delta of Egypt, the Mekong Delta (MKD) of Vietnam, or the densely urbanized deltas of the Ciliwung River (Jakarta), the Chao Pharya River (Bangkok), or the Sumida River (Tokyo), a large part of many countries' gross domestic product (GDP) is generated in these geographically important regions (Overeem and Syvitski, 2009). At the same time, however, river deltas are highly-vulnerable socio-ecological systems.

A socio-ecological system in this context is understood as a bio-geophysical unit and its associated social actors and institutions (Glaser et al., 2008). River deltas face a multitude of challenges, such as anthropogenic water, soil, and air pollution (Kuenzer et al., 2014b, 2014a; Renaud and Kuenzer, 2012; Renaud et al., 2013), a decline of biodiversity and ecosystem health (Hossain et al., 2016; Uzoekwe and Achudume, 2011), land subsidence (Higgins et al., 2013, 2014), and especially in recent decades, climate change-driven sea level rise (Auerbach et al., 2015; Dasgupta et al., 2009; Ericson et al., 2006; Phillips, 2018). Sea level rise is also one of the main drivers of salinity intrusion in deltas (i.e. the influx of saltwater into areas that are usually not exposed to high levels of salinity), which poses one of the most existential threats to delta systems (Rahman et al., 2019; Zhang and Zhao, 2010). At the same time, sustainable and integrated land-use planning is extremely challenging in these dynamic environments. Therefore, it is no surprise that in recent years, river deltas have moved into the focus of international research efforts both in the natural and social sciences and captured the attention of global and local decision makers and stakeholders (Foufoula-Georgiou et al., 2011; Kuenzer, 2013).

For instance, initiatives such as the complementary World Estuary Alliance, the Delta Alliance (both merged recently), the Connecting Delta Cities network, the Lagoons Forum and the Delta Coalition established during the Third United Nations Conference on Disaster Risk Reduction in Sendai, Japan, in March 2015 are all centred around applied research, network building and information sharing to assess large river deltas and estuaries and to explore possible solutions to existing and emerging problems. Research projects under the Future Earth platform, such as Future Earth Coasts, emphasize the importance of cross-disciplinary research in river deltas (links to the websites for all of the above stated initiatives are provided under 'web references' at the end of the reference list).

Simultaneously to these growing international efforts, the scientific community has been moving towards a more holistic and cross-disciplinary approach to delta research, where deltas are considered as social-ecological or natural-human systems (Brondizio et al., 2016b; Glaser et al., 2008; Lloyd et al., 2013; Renaud et al., 2016; Sebesvari et al., 2016; Virapongse et al., 2016). Examples of initiatives for more holistic and interdisciplinary delta research include Renaud et al. (2013), who discuss the threatened state of the world's major deltas Foufoula-Georgiou et al. (2011) who published a collaborative call for an 'International Year of Deltas' (2013) or the 'Sustainable Deltas Initiative', which sets a common vision and research agenda for scientists working on different aspects of delta research (Brondizio et al., 2016a).

An ongoing challenge for holistic assessment of risk, vulnerability or resilience of river deltas is the complexity arising when accounting for an increasing number of social, ecological and economic subsystems and their corresponding interactions. Consequently, it is not surprising that the systematic review of 54 vulnerability assessments in large river deltas of Wolters and Kuenzer (2015) found that the vast majority of assessments are strongly-focused on a single subsystem, (i.e. ecologic, social, or economic), as well as only a single threat affecting this subsystem (e.g., sea level rise). The majority of studies focus on the ecological subsystem, whereas multi-component, multi-process risk and resilience assessments, such as the climate change risk assessment for the MKD of IMHEN (2013), remain the exception (Wolters and Kuenzer, 2015). Further, there are few studies that provide a consistent quantification and comparison of risk or resilience across multiple large river deltas. A notable exception is the assessment of Tessler et al. (2015), who quantified risk and sustainability across 48 major river deltas across the world, or the comparative assessment of delta vulnerability for the Mekong, Ganges-Brahmaputra and Amazon delta (Szabo et al., 2016). In the main, the above studies focused on a single core threat/process (i.e., flooding for the former, population dynamics for the latter) and true multi-component, multi-process-based assessments of risk or resilience across multiple large river deltas are lacking.

To address this gap, the main goal of this paper is to generate comparable cross-sectoral resilience profiles for the MKD, YaRD, Yellow River Delta (YeRD), and Rhine Delta (RHD) and their inhabitants. While resilience of a system is commonly understood as the capacity of that system to recover from adverse events in a timely manner (including in this analysis), the exact definition/interpretation of resilience can vary substantially in practice and across disciplines (Linkov and Trump, 2019; Linkov et al., 2018). Resilience profiles are generated using a qualitative approach, compiling multiple years of cross-sector research undertaken in each delta via workshops and structured expert interviews. Importantly, we purposely focus on resilience rather than vulnerability or risk (as the product of threat, vulnerability and consequences), since this provides a solution- or management-oriented point of view, in line with Linkov et al. (2014), who suggest that: 'resilience, as a property of a system, must transition from just a buzzword to an operational paradigm for system management, especially under future climate change'.

Whereas vulnerability studies typically focus more on threats to a system, resilience-focussed studies tend to emphasize factors that increase resilience, meaning the coping with and adaptation to adverse events in an efficient manner. Resilience focused studies typically provide a set of recommendations for actions that will increase the ability of system to absorb and recover from the impacts of future adverse events. In other words, we focus on resilience because it is a positivistic approach, allowing a focus on 'what can be done to make things better,' (i.e. measures for increasing social and ecological resilience), rather than elaborating on 'how vulnerable are we?'. Although vulnerability assessments for individual river deltas have been undertaken by a large variety of authors (amongst others Burton and Cutter (2008), Chen et al. (2013), Clement (2013), El-Raey (1997), Frihy (2003), Ge et al. (2013), Rasul et al. (2012), Tri et al. (2013), Wolters et al. (2016), and Woodroffe (2010)), of the 54 studies reviewed in Wolters and Kuenzer (2015), few have focused on delta resilience. One exception is a comprehensive study published as grey literature reports by Bucx et al. (2014 & 2010), which compared the vulnerability and resilience of fourteen deltas globally.

The MKD, YaRD, YeRD, and RHD were selected for two reasons. Firstly, many of the authors have long-term and extensive on-ground work experiences in these deltas via multiyear interdisciplinary research and development projects. Secondly, these deltas cover a representative range of socio-economic development levels (i.e. MKD: a rural delta in an emerging country, YeRD: a rural delta in an emerging/emerged country, the YaRD: a very strongly urbanized delta in an emerging/emerged country, and the RHD in a densely populated industrialized country). In this paper, we take a qualitative approach to profile delta resilience, since the dramatic differences in the level of socio-economic development and availability of data for characterizing the social, natural and economic sub-systems strongly hinder the generation of comparable resilience profiles based on a quantitative approach. The main questions that this paper aims to answer are:

- What are the key threats confronting the MKD, YaRD, YeRD and RHD? Can these threats be differentiated depending on their origin

and driver? What is the level of exposure of each delta to different threats?
- Which factors define and – if adequately addressed – could help to increase the social resilience of a delta population? Which similarities and differences do resilience profiles exhibit for the four deltas?
- What options for coping with and adapting to threats are most commonly proposed by delta populations, scientists, and stakeholders? How do coping and adaptation profiles differ across the four river deltas?

## 2. Terms and definitions

Terms such as risk, hazard, threat, exposure, vulnerability, resilience, coping, and adaptation are frequently used in social sciences studies as well as in cross-sector studies aimed at assessing the state of a socio-ecological system. As multiple definitions exist for each of these terms, we briefly provide the definitions that we adopted here. Our definitions are in line with the ones adopted by the systematic review on delta vulnerability assessments of Wolters and Kuenzer (2015). In popular use, the term 'risk' puts emphasis on the concept of 'chance or possibility' (e.g., 'the risk of an accident', 'the risk of losing money'), whereas in technical settings, emphasis is usually placed on the consequences or potential losses for a particular cause, place and time period (e.g., 'the risk of flooding in river deltas'). According to the United Nations International Strategy for Disaster Reduction (UNISDR) terminology, risk is the 'combination of the probability of an event and its negative consequences' (UNISDR, 2009). Here, we adopt this definition for the term 'risk'.

A 'hazard', according to UNISDR is 'a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009).' According to Turner et al. (2003) hazards 'are threats to systems, comprised of perturbations and stress'. The term 'hazard' is often associated with sudden or slow-onset natural events (such as earthquakes, tsunamis, cyclones, droughts) or technological calamities (such as nuclear accidents, chemical spills, fires). In this paper we use the term 'threat' rather than hazard, as we think that there are numerous stressors impacting river deltas that are not typically associated with the term 'hazard'. The multitude of natural and anthropogenic stressors affecting river deltas, such as for example the replacement of mangrove forests with aquaculture, can be better approximated with the more general term 'threat'. 'Exposure' is defined as per Gallopín (2006) as the 'general degree, duration, and/or extent in which the system is in contact with, or subject to, the perturbation'. For example, there are regions highly exposed to the threat of earthquakes (Pacific Rim etc.), while other areas might rather be highly exposed to the threat of hurricanes (Caribbean, Southeast Asia, etc.).

'Vulnerability' can be defined as 'the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard/threat.' (UNISDR, 2009). There are generally many aspects of vulnerability arising from various social, economic, and environmental factors, and these can vary significantly within a community and over time. Here, we define vulnerability in line with Gallopín (2006), who defines it as the 'susceptibility to harm, a potential for a change or transformation of the system when confronted with a perturbation, rather than the outcome of this confrontation.' Other definitions focus on vulnerability within a certain sphere, such as the Intergovernmental Panel on Climate Change (IPCC), which defines vulnerability as the 'degree a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. In the context of climate change, vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity' ( IPCC , 2007).

Importantly, exposure and vulnerability are closely linked. As Gallopín (2006) puts it, 'a system that is not exposed to a perturbation would be defined as non-vulnerable'. At the same time, although a system may be very vulnerable to a certain perturbation (threat) it might be able to 'persist without problems insofar it is not exposed to it' (Gallopín, 2006). For example, a city located far inland might be very vulnerable to a tropical cyclone but can persist without any problem as long as it is not actually exposed to one. Instead of focusing on vulnerability, however, the focus of this paper is on the 'resilience' of river deltas.

Resilience is a term originating in the technical sphere (e.g., engineering resilience as the 'return time to a steady-state following perturbation, 'Holling (1973) and is understood here as 'the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions' (UNISDR, 2009). In general terms, resilience refers to the ability of a system to 'recover from' an adverse event/risk (Linkov et al., 2014). The resilience of a community in respect to potential threats is determined by the degree to which the community has the necessary resources and is capable of organizing itself both prior to and during adverse events. As Walker et al. (2003) states, resilience is 'the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks.' Importantly, due to the conceptual nature of the term, exact definitions of resilience still vary substantially in the academic literature and Linkov et al. (2018) argue that different disciplines might eventually adopt different conceptualizations of resilience.

Some authors differentiate between ecological, social (individual) and societal resilience. For instance, Gunderson (2002) defines ecological resilience as the 'magnitude of disturbance that a system can absorb before it flips into another stability domain (alternate regime) by redefining structures and changing variables and processes,' and others add 'A resilient ecosystem can withstand shocks and rebuild itself when necessary (Resilience Alliance, 2020).' Simpson (2002) defines social resilience as the ability of groups or communities to cope with external stressors and disturbances (i.e. which originate outside of the delta) as a result of social, political, and environmental change. However, the ecological and social spheres are closely-intertwined and subjected to a multitude of feedback loops, and as the Resilience Alliance states, 'resilience in social systems has the added capacity of humans to anticipate and plan for the future (Resilience Alliance, 2020).' As humans, we are part of the natural world and, as such, we depend on functioning ecological systems for our survival. On the other hand, human development continues to adversely impact the ecosystems in which we live both on local and global scales, thereby undermining many essential ecosystem services such as the provision of food, clean water or the protection from natural hazards. Therefore, resilience should always be understood as a joint property of linked social-ecological systems (SES), rather than a feature of isolated ecological or social systems' (Walker et al., 2003).

Especially in the field of climate change, numerous authors have addressed the topic of increasing resilience via an increase in coping capacity and tailored adaptation measures. 'Coping' in the context of this study is understood as the capacity of a system to cope or respond in the short term, whereas adaptation refers to the capacity to adapt in the medium- and long-term. Fig. 1 illustrates this definition, with coping occurring immediately during and after external disturbances for a limited amount of time, while the adaptation process is continuous, spanning across subsequent disturbances. UNISDR defines coping capacity as 'the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters. The capacity to cope requires continuing awareness, resources and good management, both in normal times as well as during crises or adverse conditions.' Adaptation on the other hand, is understood as 'the adjustment in natural or human systems in

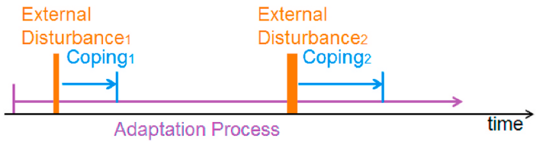


**Fig. 1.** Conceptual diagram illustrating the difference between coping and adaptation of a system to a series of external disturbances. The second external disturbance is more severe than the first, leading to a longer coping time. If adaptation occurs, a third external disturbance of the same magnitude as the second disturbance will be dealt with in a shorter coping timeframe.

response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities' (UNISDR, 2009). The IPCC (2007) understands adaptation as 'initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects,' and adaptive capacity as 'the whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.'

## 3. Assessment sites: Mekong, Yangtze, Yellow River, and Rhine deltas

The study areas are only introduced briefly, as comprehensive descriptions including the environmental challenges in the four deltas have been previously published by members of our authors' group (Bucx et al., 2014, 2010; Kuenzer et al., 2014a; Ottinger et al., 2013; Renaud and Kuenzer, 2012; Varis et al., 2012; Vo et al., 2012; Yang et al., 2015). The study areas are depicted in Fig. 2.

### 3.1. Mekong Delta

The MKD is situated at the river mouth of the more than 5400 km long Mekong River. Within the 39,000 km$^2$ delta, the Mekong is divided into nine arms draining into the ocean. Some 17 M inhabitants populate the delta, which is often termed the 'rice bowl' of Southeast Asia. It is the 'breadbasket' of Vietnam, with 50% of the country's internally-consumed rice, 60% of its fruits, and 60% of its seafood produced there. The delta landscape is characterized by large rice paddy fields, fruit tree orchards, aquaculture dominated coastal zones, and decreasing mangrove forests along the coastline. Cities and towns are scattered throughout the delta – the largest being Can Tho with about 1.5 M inhabitants, but overall, the delta resembles a rural landscape. Sea level rise, salinity intrusion, frequent annual floods, the increasing occurrence of droughts, upstream hydropower dams, water diversion and subsidence, as well as the consequences of rapid socioeconomic development trouble the delta inhabitants, who are subjected to a water hydrocracy-impacted decision making elite. (Kuenzer et al., 2013a, 2013b; 2013c, 2011; Kummu and Varis, 2007; Renaud and Kuenzer, 2012; Vo et al., 2012).

### 3.2. Yellow River Delta

The YeRD is the river mouth area of the 5464 km long Yellow River, the second longest river of China and the river with the highest sediment load worldwide (Kuenzer et al., 2014a). The delta is located in China's Shandong Province and spans an area of 10,000 km$^2$. About 6 M people live in Dongying district, which comprises the main delta area and is also home to Dongying City, the largest city of the delta. The fate of the delta will strongly depend on the balancing of the delta's two major assets into

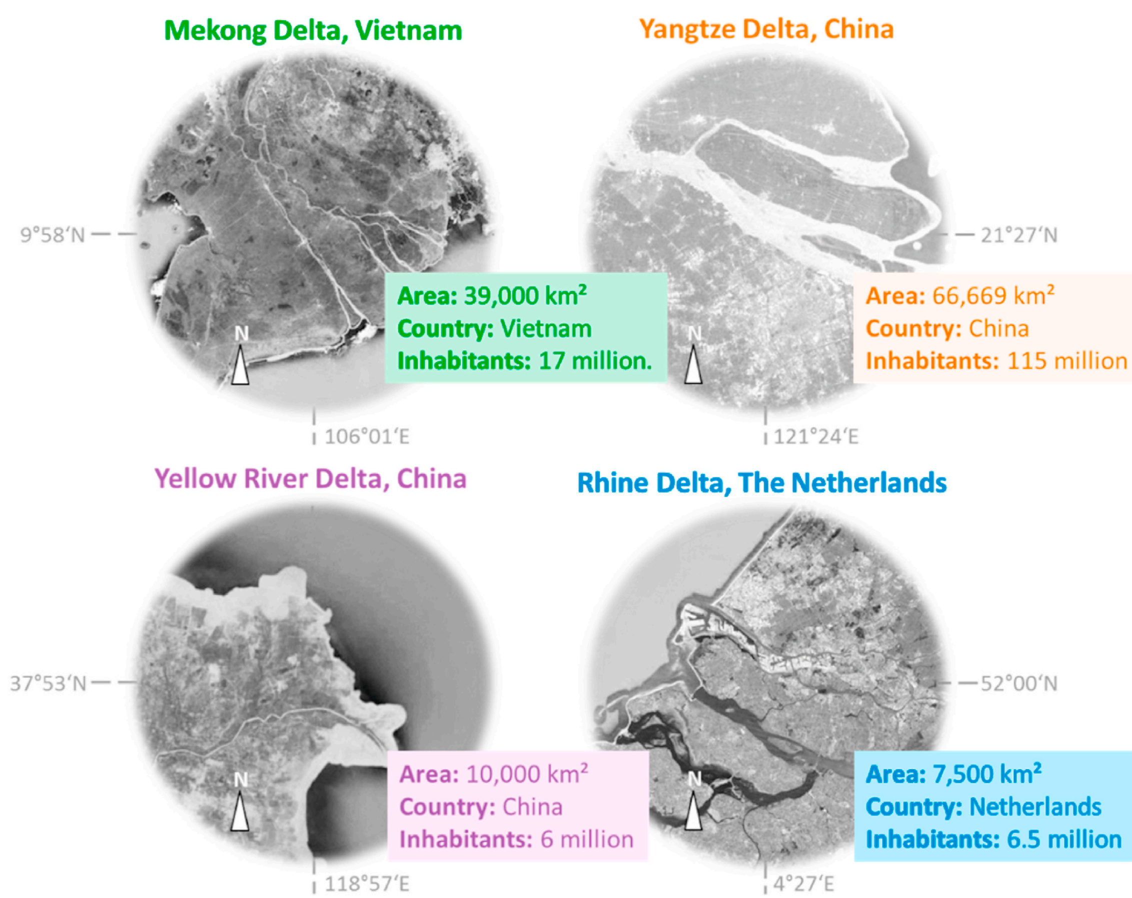


**Fig. 2.** The four assessment sites: the Mekong-, Yellow-, Yangtze-, and Rhine deltas, in Vietnam, China, and the Netherlands, including information on delta area and number of inhabitants. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the future. The YeRD is part of the Shengli oil field, which is China's second largest oil field. Hundreds of oil and gas pumps extract the valuable underground reserves within and outside the delta's local Gudong Oil Field production area. At the same time, the delta is home to two large nature reserves, which host a rich biodiversity including 1917 animal and plant species as well as 269 bird species (Cui et al., 2009). The delta, and especially the nature reserves, which were declared Ramsar wetland sites in 2013, are an important resting place for migrating birds, including about 152 protected species (Cui et al., 2009; Eryong et al., 2009; Wang et al., 2010; Xu et al., 2009). Ottinger et al. (2013) have demonstrated the ongoing land use change in the delta over the past few decades, which are strongly dominated by economic development rather than the protection of natural resources. Further, Kuenzer et al. (2014a) analyzed coastline changes caused by technocratic river redirection, oil pump spread, and noncompliance with protection regulations in the delta. They found that some parts of the delta have retreated by over 13 km, while other parts have accreted by over 21 km.

### 3.3. Yangtze River Delta

The YaRD is situated where the 6300 km long Yangtze River drains into the East China Sea. The triangular shaped area comprises parts of Shanghai, southern Jiangsu Province, and northern Zhejiang Province in China. The YaRD covers an area of around 70,000 km$^2$ and is inhabited by over 80 M people, half of which live in urban centres (Ge et al., 2013). The GDP of this region exceeds two trillion USD, which accounts for about 20% of the entire country's GDP (Anthony, 2014; Renaud and Kuenzer, 2012). With a population density of 2700 inhabitants per km$^2$, the delta is one of the most heavily populated regions on earth.

Major cities in the delta include Shanghai, Nanjing, Hangzhou, Suzhou, Ningbo, Nantong, Wuxi, Changzhou, Zhoushan, Jiaxing, Zhenjiang, Huzhou, and Shaoxing. Of these cities Shanghai stands out, as being one of the cities with the largest land reclamation programs worldwide. Over 100,000 ha of land have been claimed from the sea/estuary in the past 50 years, and the process is ongoing (Shen et al., 2013). In recent years, large increases in the concentration of fertilizer-derived nutrients in the Yangtze River has led to dramatic algal blooms, triggering decreasing oxygen levels of water resources and an associated decline in fluvial, estuarine and marine ecosystem health and productivity. Additionally, the Huangpu River, which flows through Shanghai City, and four sewage outlets from that city, discharge directly into the Yangtze estuary, which covers the most downstream parts of the delta. Shanghai especially suffers from severe ground subsidence due to groundwater pumping and recent sediment compression caused by high rise building construction. Aggravated by natural crustal movements and sea level rise, this development poses a severe threat to the delta population (Chen and Zong, 1999). Subsidence of 1.76 m was observed in the city between 1921 and 1965, and subsidence has continued at a similar rate during the subsequent years (Bo et al., 2010; Chen and Zong, 1999; Chu et al., 2006; Dai et al., 2008; Zhang et al., 2019).

### 3.4. Rhine Delta

The RHD (sometimes also called the Rhine-Meuse-Scheldt Delta) is located in the western Netherlands and north-eastern Belgium and is characterized by a multitude of river branches, canals, and islands. It has significant economic importance as it is the entry point of shipping routes to the vast German and Central European hinterland from the North Sea. Originating in Switzerland, the Rhine flows through Germany for most of its course. Close to the delta, it crosses into the Netherlands, where the river splits up into the 'Nederrijn' (lower Rhine) (28.6% of the water) and the Maas (71.3% of the water). Cities such as Dordrecht, Rotterdam, and Den Hague, amongst others, are located in the 7500 km$^2$ delta. The population of the delta area includes approximately 6.5 M inhabitants. Dense urban areas alternate with agricultural land and the delta is protected from flooding by the Dutch delta works. These delta works are one of the largest coastal protection infrastructure in the Netherlands, consisting of dams, dykes, sluice gates, locks, levees and storm surge barriers built to shorten the Dutch coastline and protect the low-lying hinterlands. Before the delta works were built, tidal influence reached as far inland as Nijmegen (107 km inland from the coast, and over 160 river km from the river mouth), and even nowadays, tidal influence can be felt up to the city of Brakel, 60 km (linear distance) from the coast, or 85 river km from the river mouth (Gouw and Autin, 2008; Törnqvist, 1993; Vellinga et al., 2014).

## 4. Profiling delta resilience

### 4.1. A conceptual framework for delta resilience

A meaningful quantification of resilience and comparison thereof across different river deltas requires a sound conceptual framework of a river delta's general functioning and the role of resilience and threats in that. For this purpose, we adopted Wolters and Kuenzer (2015) conceptual framework, as depicted in Fig. 3-A, in which a river delta system is made up of an ecologic (the delta's natural system: green in Fig. 3), social (livelihoods, humans, governance in the delta: yellow in Fig. 3), and economic subsystem (economic activity, industry, purple in Fig. 3). The boundaries between the subsystems are hardly ever rigid, as indicated by the gradual color transitions. The color of the triangle in the middle of each situational plot in Fig. 3 depends on the state of the delta system (in order of decreasing resilience from green to yellow to light orange to dark orange). The overall state of the delta also depends on the impact of internal and external threats (black arrows). Each delta, including its subsystems, and the components therein, has a certain coping capacity (the area between the outside dashed line and the inside dot-dash line, which indicates the point-of-no-return threshold) and a certain adaptive capacity (grey perimeter zone).

To describe the various possible states in which a real-world delta might currently exist, six threat and resilience scenarios/situations are used (Fig. 3, Situation A-F). Situation 'A' depicts a healthy, fully resilient, delta state, where no threats that cannot be compensated or mitigated are currently impacting the delta, and where coping and adaptive capacity are fully intact and in balance with (or compensating) the threats. The delta and its subsystems have the highest degree of resilience. In situation 'B', threats start to impair the delta but the delta can still cope with the threats. Its overall state is still 'healthy' and resilient, and the limits of coping and adaptive capacity are not exceeded. In situation 'C', threats disturb the ecologic delta subsystem substantially, with the social subsystem being affected as well. The whole system is less resilient to threats than in the previous two situations. This system has a degraded coping capacity, but adaptation is still possible. In some cases the coping capacity may be restored (situation 'D' compared to 'C'), but quite often, ongoing or repeated threats continue to impair the delta's three subsystems and resilience is substantially decreased, as indicated by the near breaching of the coping capacity threshold in Situation 'E'. In this situation, all three systems are seriously affected by threats, and the threshold beyond which any recovery from negative impacts is no longer possible is nearly reached. Situation 'F' depicts a completely degraded delta (dark orange triangle), where especially the social and economic system coping capacity have been eroded beyond critical thresholds. The river delta system is at risk of complete collapse or transition into a new, less desirable, and less productive overall state.

### 4.2. Establishing resilience profiles

Profiling or quantifying river delta resilience or vulnerability is complex. Each of the three aforementioned sub-systems (i.e. economic, ecologic and social) that comprise a river delta can theoretically be subdivided into a near infinite number of smaller and smaller subsystems. For instance, the ecologic subsystem could be subdivided to the

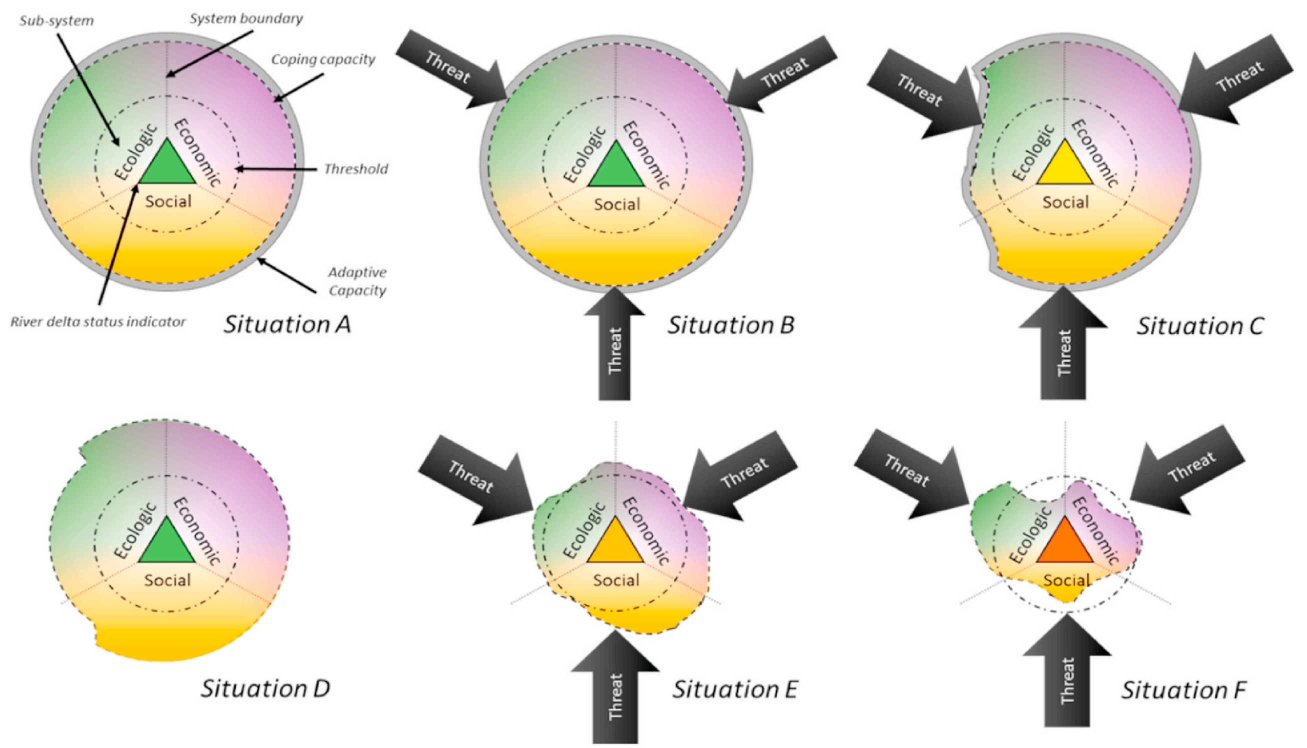


**Fig. 3.** Graphical representation of the state of resilience of a river delta system. Adapted from Wolters and Kuenzer (2015).

level of individual species (i.e. types of mangroves, saltmarsh or fish), each with individual resilience levels in regard to different environmental stressors, such as increases in water temperature, sea level rise or salinity. However, the goal of this study was to generate and compare resilience profiles for four large river deltas that encompass all core components that contribute to the proper functioning of these systems. As such, a delta-wide, holistic resilience assessment requires some degree of simplification. Further, due to a scarcity of data to consistently quantify resilience across key components of the ecologic, social and economic subsystems across four deltas located in different countries and with different stages of socio-economic development, only a qualitative, expert-guided approach is suitable for establishing a meaningful comparison.

Here, we adopted a novel approach, where resilience assessments were undertaken through structured and semi-structured interviews and criteria rankings during extensive and repeated field campaigns to each delta during three consecutive years from 2011 to 2013, as well as during meetings, workshops and conferences focusing on coastal and river delta affairs. For each delta area, 12 experts were interviewed by the authors. The interviewees were a mix of decision makers, stakeholders, scientists, and experts (people working at NGOs, etc.), all highly-familiar with the respective deltas via international projects, field campaigns or in-depth scientific and personal exchanges. However, it must be noted here, that the mix of experts interviewed was not fully equal, which is however expected, given the complex geographical research setting. All authors have been involved in research of the MKD in Vietnam for over a decade, while YeRD research lasted for about six years, YaRD research for less than 3 years, and the RhD was visited sporadically (mainly also during visits of other delta stakeholders in Europe, or during conferences and scientific workshops). This means that access to stakeholders, institutions, and interviewees was not equal. Access to stakeholders at ministerial level etc. (e.g. in the Netherlands) is not necessarily granted just because a research consortium is interested in organizing meetings or workshops. Furthermore, the funds of a research consortium (travel, time in the countries, length of the study period enabling the development of close, trust-based relationships at all levels) is also limited. In some of the deltas, the collection of objective expert opinion was further complicated by the political sensitivity inherent to the governmental management of risk and resources in these settings.

Table 1 provides an overview of the diverse range of institutions and background of the respective interviewees in each delta. Additional participants (not interviewees) in this process were six of the nine

**Table 1**
Overview of institutions/background of the interviewees in each river delta.

| Mekong Delta | Yellow River Delta | Yangtze River Delta | Rhine Delta |
|---|---|---|---|
| Can Tho University | Dongying Municipality Sustainable Development Research Institute of the Yellow River Delta | Tongji University Shangai | Delft University |
| Peoples Committee Can Tho | | Changjiang (Yangtze) Water Resources Comission | University of Hannover |
| Ministry of Environment, MONRE (national and district) | Yellow River Delta Natural Wetland Reserve | Institute of Geography and Natural Resources Research, IGSNRR der CAS, Beijing | Deltares |
| Ministry of Agriculture and Rural Development, MARD (national and district) | Yellow River Conservancy Commission | Institute of Remote Sensing Application, IRSA, CAS, Beijing | ITC |
| Southern Institute of Water Resources Research, SIWRR | Institute of Geography and Natural Resources Research, IGSNRR der CAS, Beijing | Local fisherman | Local inhabitants |
| Institute of Geography, VAST-GIRS | Institute of Remote Sensing Application, IRSA, CAS, Beijing | – | – |
| GIZ Vietnam | Local fisherman | – | – |
| Local rice farmer | – | – | – |

authors of this study, all of whom have been to and worked in the four deltas discussed here and have been engaged in delta research for many years.

Initially, parameters were defined, including the classification of threats affecting river deltas into internal and external threats (and types of threats). A list was also compiled of the most frequent and representative threats. Furthermore, this definition stage included the fixation of parameters defining the resilience of a river delta population, as well as the adaptation options commonly undertaken in the selected river deltas to boost that delta's resilience. In a second step, experts then quantitatively ranked the selected parameters on a scale from 1 to 5 (very low, low, intermediate, high, very high). This ranking was undertaken based on long-term expert knowledge, as well as on statistical yearbook information of the respective delta countries or provinces.

## 5. Results of the comparative assessment

### 5.1. External threats affecting deltas

During the generation of the threat profiles for each delta, it became evident that external and internal threats needed to be differentiated. For clarity, external threats originate outside of the delta, with the most important external threats, as identified during repeated group discussions, presented in Table 2. An external threat to a delta (arising not from within the delta) is for example an arriving Tsunami wave, originating far away from the delta or an oil spill arriving at the delta's coast, which has been induced by a technical accident in an offshore installation further away.

As explained in Section 4.3, each threat was ranked based on a structured integration of expert knowledge (from 1 to 5: very low, low, intermediate, high, very high). The resulting external threat profiles for the four river deltas (MKD, YeRD, YaRD, RHD) are shown in Fig. 4.

**Table 2**
Delta threats of external origin and what is inducing them (listed in arbitrary order).

| | Delta threat of external origin | The threat is induced by: |
|---|---|---|
| 1 | Sea level rise and salinity intrusion | Climate change |
| 2 | Storm surges | Low pressure systems and cyclones over the ocean or near the coast |
| 3 | Tsunamis | Ocean floor quakes initiating large flood waves |
| 4 | Offshore oil spills | Accidents on ships, oil rigs and platforms |
| 5 | Allochthonous sea water pollution | Effluents not originating in the delta |
| 6 | Allochthonous air pollution | Exhausts from cities or industry outside of the delta |
| 7 | River water shortages | Uptake or diversion of irrigation or drinking water upstream |
| 8 | Upstream related floods | Upstream diking, water release/spills from dams, etc. |
| 9 | Water pulse changes and fluctuation | Dam operation and water control upstream |
| 10 | Changed sediment dynamics and loss | Upstream dams and barriers leading to sediment retention |
| 11 | Water pollution | Settlement, industrial, agricultural waste and runoff from upstream |
| 12 | Droughts | Regional scale seasonal to decadal climate variability |
| 13 | Food shortages or price instability | Markets outside the delta strongly driving crop patterns |
| 14 | Political conflict | Conflict driven into the region via transboundary processes |
| 15 | Epidemics | Epidemics in areas outside the delta that are carried into the region |
| 16 | In-migration triggering resource-competition | Push factors outside the delta leading to migrations to the delta |
| 17 | Extensive tourism | Strain on resources |
| 18 | Unsound planning, corruption, nepotism | External water hydrocracy elites that drive decision making |

Despite their qualitative origin, the profiles draw a clear picture of the dominant external threats affecting each delta, as well as the major differences amongst them.

The threat posed by sea level rise is common to all four deltas, but the effects are especially strong in the MKD and YaRD, whereas the YeRD and RHD are considered to be less affected. For the MKD, climate models project a sea level rise of 32 cm by 2050 for moderate emission scenarios (Carew-Reid, 2008; MONRE, 2009). Salinity intrusion into the hinterland is already a severe problem here leading to the abandonment of former rice crop systems and a general shift of agro-ecosystems (Rozema, 2010). The threat of sea level rise in the MKD is aggravated by a severe loss of mangrove forests (Kuenzer et al., 2011; Schuerch et al., 2018; Vo et al., 2012), the extreme expansion of aquaculture (Genschik, 2014) (no buffer zones along the coast to weaken the impact of storm surges), and upstream-induced sediment depletion (Kuenzer et al., 2013a). In this case, sea level rise threatens the rural livelihood of 17 M inhabitants. In the YaRD, sea level rise is evenly and strongly accentuated, but in this case, large agglomerations (Greater Shanghai Urban Area) are at risk, with much of the area (e.g., the economic center of Pudong) already located well below sea level. Significant investments into underground water storage basins and pumping systems are needed to protect the area from sea level rise-driven flooding, especially during storm surges (Lau, 2004). For the YeRD and RHD, sea level rise is perceived as a high threat, but to a lesser degree than in the other two deltas. Predicted sea level rise in the YeRD is lower than that in the YaRD, as the YeRD is located in a separated bay with limited tide variation (i.e. due to regional to global scale variations in mean sea level and sea level rise). Further, in the less densely populated areas, fewer people are affected, and the dependency of rural livelihoods is not as pronounced as in the MKD. In the RHD, where sea level rise is progressing rapidly along the North Sea coast, the Dutch delta works, long-time sea level rise awareness and even-handed consideration of coastal retreat scenarios (Rozema, 2010) may reduce the threat of sea level rise. Storm surges are a medium-level threat to the MKD, YaRD, and RHD, whereas the YeRD – again due to its location and corresponding coastal and marine setting – is less affected.

The threat of tsunamis and their associated impacts is considered to be very low in the RHD, low in the YeRD, and medium in the YaRD and MKD. Offshore oil spills are a very high threat in the extensively explored surroundings of the YeRD, a less severe threat in the YaRD and MKD, and a low threat in the RHD. Water pollution and air pollution are very high threats in the YeRD, and the YaRD. Water and air pollution are much less pronounced threats in the MKD and the RHD than in the two Chinese deltas. Upstream water diversion, floods, and flood pulse changes are among the greatest threats to the MKD (Kuenzer et al., 2013) and severely impact the YeRD, where in the 1990s and early 2000s, no upland inflows reached the delta for up to 220 days within each year due to excessive upstream storages and diversions. The RHD does not experience any major upstream-induced pulse or sediment changes that impair the ecologic, social, or economic subcomponent of the delta. Additionally, no major dams exist on the Rhine, with much of the river reclaimed and some of the natural retention spaces restored in the past two to three decades. The threat of food security teleconnections exists mainly in the three Asian deltas with their steeply increasing levels of consumption. Whereas the RHD mainly produces for national and EU markets at stable levels, the YeRD has been transformed from a diverse agricultural landscape to cotton monoculture in the 1990s and early 2000s (Jiang et al., 2011), and subsequently to soy monoculture in recent times (due to the high demands of the Chinese market). The power of this large Chinese market with over 1 B consumers can also be felt in Vietnam, where in large parts of the MKD, sweet potatoes are now grown for export to mainland China.

Transboundary conflicts affect the MKD, which is shared by six riparian nations (see high rankings for upstream threats in Fig. 4), but compared to areas undergoing civil war, it can be considered a stable region, experiencing the longest spell of peace in its history (Kuenzer

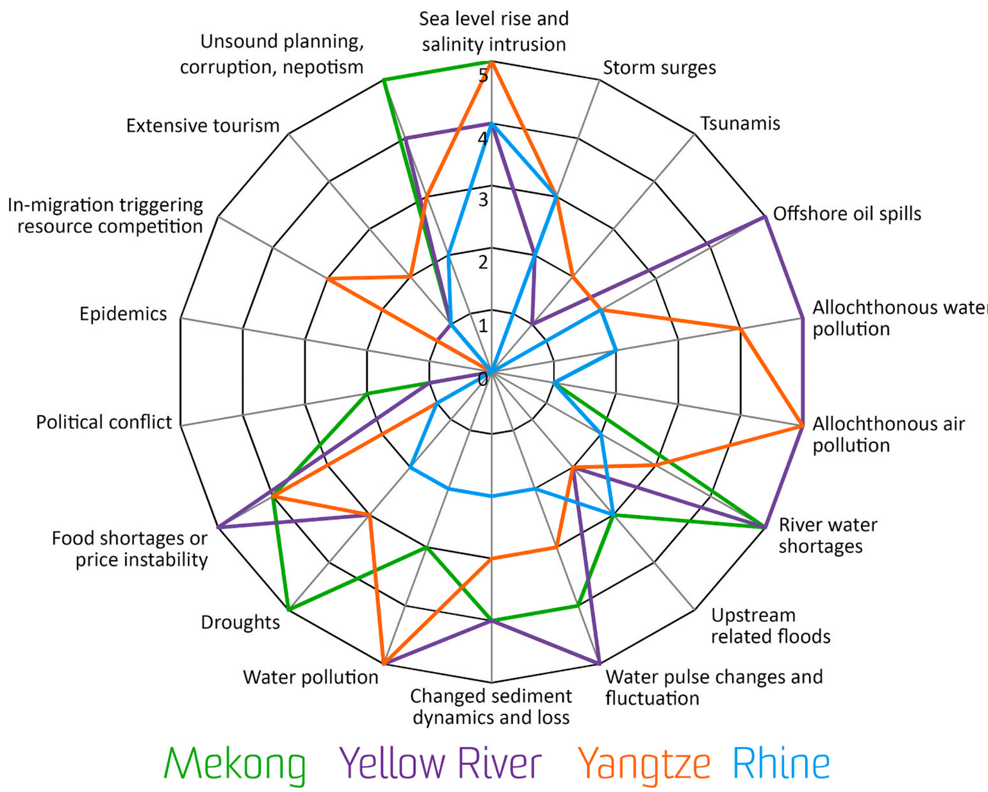


**Fig. 4.** External threat profiles for the Mekong, Yangtze, Yellow, and Rhine River deltas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2013a). Transboundary epidemics are not considered a relevant threat in any of the deltas. Whereas the MKD (Dun, 2011), YeRD, and even part of the RHD are primarily out-migration areas (or stable), the YaRD still experiences considerable growth via in-migration. Urbanization is expanding, as will the associated threats. Extensive tourism is negligible in all deltas, and even in the YaRD, where it is most prominent, it is considered a low threat. However, water hydrocracy interests (i.e. decision maker groups promoting unnecessary infrastructure projects to cater to their own financial advantage) are considered to be very pronounced in the MKD (Benedikter, 2013), high in the YeRD, and still relevant in the YaRD (medium) and RHD (low).

### 5.2. Internal threats affecting deltas

Internal threats originate from within the delta itself. Similar to the external threats, the most relevant threats were identified during repeated and systematic group discussions and an overview is provided in Table 3.

Again, each internal threat listed in Table 3 was ranked based on expert opinion and the resulting internal threat profiles for the four deltas are shown in Fig. 5. It is evident, that our approach is able to reveal the dominant internal threats affecting each delta as well as the differences among the deltas. Notably, oil spill related pollution is omnipresent in the YeRD, and also occurs in the YaRD (here industry related), whereas there are low impacts in the RHD and no impacts in the MKD (although exploration is planned). Urban, agriculture- and aquaculture-induced pollution of water, soil and air is most dominant in the Chinese deltas and has reached satisfactory levels (low threat) for the RHD. In the MKD the main driver of water and soil pollution is not so much urbanization (as in the two Chinese deltas), but rather the input of fertilizer, pesticides, hormones, and antibiotics via agriculture and aquaculture (Sebesvari et al., 2011).

Natural geologic subsidence processes, which aggravate sea level rise, exist in all four deltas, but additional subsidence is a large threat in

**Table 3**
Delta threats of internal origin and what is inducing them (listed in arbitrary order).

| | Delta threat of internal origin | The threat is induced by: |
|---|---|---|
| 1 | Oil and gas spills and related pollution | Onshore oil and gas drilling related accidents in the delta |
| 2 | Industry related water and soil pollution | Industry releasing effluents |
| 3 | Urban area related water and soil pollution | Urban areas releasing effluents |
| 4 | Agriculture related water and soil pollution | (Over-) application of fertilizer and/or pesticides |
| 5 | Aquaculture related water and soil pollution | Release of excrements, antibiotics, hormones |
| 6 | Autochthonous air pollution | Exhausts from urban areas and industry |
| 7 | Geologically driven land subsidence | Natural compaction of delta sediments |
| 8 | Structure-driven land subsidence | Compaction due to heavy structures such as infrastructure in cities |
| 9 | Ground water extraction driven subsidence and saline intrusion | Volume and pressure loss underground and replacement of fresh groundwater with saline oceanic waters |
| 10 | Oil and gas extraction driven subsidence | Oil and gas extraction leading to cavities underground |
| 11 | Coastal forest destruction | Land use expansion, resource competition, wood collection |
| 12 | Coastal wetland destruction | Land use change, land reclamation, resource collection |
| 13 | Landscape/habitat fragmentation | Changes in infrastructure and land use |
| 14 | Loss of biodiversity, habitats, natural feed | Monoculture expansion and destruction of natural resources |
| 15 | Decline of fish and wildlife catch | Overfishing and wildlife collection |
| 16 | Brain drain, loss of human intellectual capacity | Out-migration of the delta population |
| 17 | Barriers and hindrance of natural fluxes | Installation of dykes, sluices, expanding roads, urbanization |
| 18 | Unsound planning, corruption, nepotism | Internal water hydrocracy elites that drive decision making |

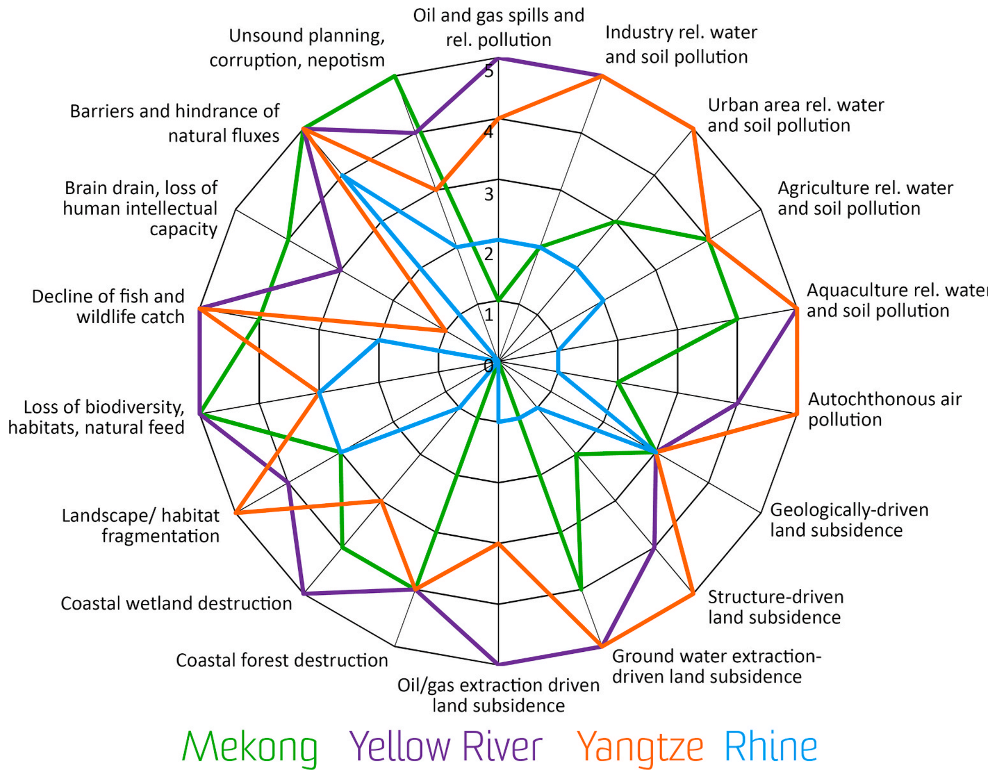


**Fig. 5.** Internal threat profiles for the Mekong, Yangtze, Yellow, and Rhine River deltas. Resilience of delta societies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the YaRD and YeRD due to compaction via urbanization as well as groundwater-, oil- and gas extraction. In the MKD, only groundwater extraction currently aggravates subsidence, while infrastructure-driven compaction does not yet play a very relevant role. Coastal forest and wetland destruction as well as landscape fragmentation are high to very high threats in all three Asian deltas, largely as a result of the expansion of monoculture (including aquaculture) (Bi et al., 2011). Landscape fragmentation and loss of biodiversity are also considered relevant in the RHD. Whereas this area has a stable population, especially the YeRD and the MKD are out-migration areas (related to urbanization processes outside the delta), and highly educated students leave to seek employment in large cities such as Shanghai, Beijing, or Saigon (Kuenzer and Renaud, 2012). These patterns have indirect adverse impacts on education levels in the deltas as well as on informed decision making and good governance by local stakeholders. The latter process is often influenced by water hydrocracy interests, especially where infrastructure development is fostered (Benedikter, 2013). There is often a direct relationship between the development status of an area and its degree of informal (corrupt) decision making (https://www.transparency. org/cpi2014/results), which is why this threat is ranked as very high in the MKD and YeRD.

### 5.3. *Resilience of delta societies*

Table 4 provides a summary of the key parameters that influence the resilience of a river delta inhabitant (representing the social system). These parameters were defined based on extensive and structured discussions about what increases a delta resident's resilience to both internal and external threats.

Increasing and improving any or all of the above parameters will lead to an increased level of a resident's resilience. As presented in Fig. 6, nearly all parameters are ranked highest for the very developed RHD area. Here, delta inhabitants have a high awareness and degree of knowledge about climate change and the quality/importance of natural

**Table 4**
Parameters impacting a river delta inhabitant's resilience (listed in arbitrary order).

| | Parameter (resilience relevant) | Elaboration |
|---|---|---|
| 1 | Education level | The higher the more income and action alternatives |
| 2 | Climate change awareness | Facilitates localized/grass-roots adaptation and future planning |
| 3 | Knowledge of local water quality | May inform careful choice or treatment of intake |
| 4 | Knowledge of local food quality | May inform careful choice or treatment of intake |
| 5 | Knowledge of local soil and air quality | May inform adaptive behavior/ protection |
| 6 | Average medical knowledge | May inform correct reactions during bad health |
| 7 | Independence level of livelihoods | Not being confined to a certain location or job |
| 8 | Average local income/purchasing power | The richer the more flexibility |
| 9 | Availability of/access to (natural) resources (or ecosystem services) | Clean water, air, soil, food on one's own and public land |
| 10 | Job and income alternatives | Opportunity to find another job, generate income |
| 11 | Size of social network | Large social (family) network offers backup support |
| 12 | Spatial mobility | Ability to reach work/markets/ health care/evacuation |
| 13 | Quality of housing | The better the safer; protection against natural and social threats |
| 14 | Access to alternative shelters | Safe places during threatening situations |
| 15 | Average access to medical care | Proximity to health care |
| 16 | Medical care coverage | Medical insurance situation |
| 17 | Ability to swim | In case of threats such as storm surges or accidents |
| 18 | International focus on the area | Usually brings investment into the region |

**Table 5**
Adaptation measures impacting a river delta's overall resilience (listed in arbitrary order).
(ed: educational measures, ec: ecological measures, tc: technological measures, or combinations of these).

| | Adaptation measures |
|---|---|
| 1 | Existence of emergency response/climate change adaptation bodies and plans (tc, ed, ec) |
| 2 | Enforced emergency response/climate change adaptation bodies and plans (tc, ed, ec) |
| 3 | Existence of strict, high standard environmental laws and regulations (ed) |
| 4 | Enforcement of high standard environmental laws and regulations (tc, ed) |
| 5 | Existence of mandatory, high quality overall and environmental education (ed) |
| 6 | Existence of a health insurance network, first aid support and disease control (ed, tc) |
| 7 | Provision of access to (mandatory) health support, first aid and disease control (ed, tc) |
| 8 | Functioning network of high-quality water supply and treatment plants (tc) |
| 9 | Network of solid dykes and/or other protective infrastructure (tc) |
| 10 | Well distributed hydrologic and pollution monitoring networks (tc) |
| 11 | Adequate supply of flood retention space (ec) |
| 12 | Well maintained water and land transport infrastructure (tc, ed) |
| 13 | High standard environmentally safe industry (tc, ed) |
| 14 | Coastal forest/wetland protection, restoration and reforestation activities (ec, ed) |
| 15 | Establishment of protected areas and nature reserves (ec, ed, tc) |
| 16 | Encouragement of or ongoing ecotourism (ed, ec) |
| 17 | Introduction of salt tolerant/resilient crops, sustainable agro-ecology (ec, ed) |
| 18 | Promotion of an energy saving lifestyle with a small ecologic footprint (ed, ec, tc) |

resources, have excellent mobility, high quality housing, access to shelters and medical care, and due to a relatively high education and income level, their livelihood dependence is less acute and income alternatives exist. Resilience is notably reduced in the YaRD, even lower in the YeRD, and lowest in the MKD. Not surprisingly, a direct relationship seems to exist between a delta's degree of social-economic development and the average degree of resilience of a delta resident. However, there is one aspect where the Asian deltas – and here especially the MKD – have an advantage over well developed areas such as the RHD; the size of a person's social network. A large network of direct family and more distant relatives provides an indirect buffer against threats, as someone with a large social network can, in most cases, count on shelter/food/support from family members during an emergency. In an aging society such as is common in most of Europe (average age in 2011 in the Netherlands: 41.1 years versus Vietnam: 27.8 years (CIA, 2014), with declining birth rates (German crude birth rate: 8.42/1000 in 2014 versus a birth rate in Vietnam of 16.26/1000) (CIA, 2014), family networks are inevitably shrinking.

### 5.4. Adaptation in deltas

As elucidated by Kuenzer and Renaud (2012), adaptation measures to increase resilience of a river delta can consist of technological, ecological, educational, and political measures that can safeguard and maintain or even improve the state of the natural, social, or economic subsystem of the delta. Technological measures can be the installation of infrastructure such as coastal defense structures, dykes, sluice gates, pumping systems, the weather-proofing of harbors, the establishment of back-up water supplies, wastewater treatment, or water desalinization plants, the introduction of energy saving technology, the development of early warning systems, the construction of emergency shelters including supply stocks, and a storage bank of adapted crop species. Ecological measures are all measures fostering the health and abundance of deltaic ecosystems, such as the restoration of degraded ecosystems, planting of salt-tolerant/drought-resistant species, coastal reforestation, the establishment of nature reserves or protection zones, as well as the adoption of eco-certificates or payments for ecosystem services. Educational measures include education on the environment, climate change, first aid and medical preparedness, disease control, swimming lessons, and all efforts undertaken to strengthen specific awareness of the value of

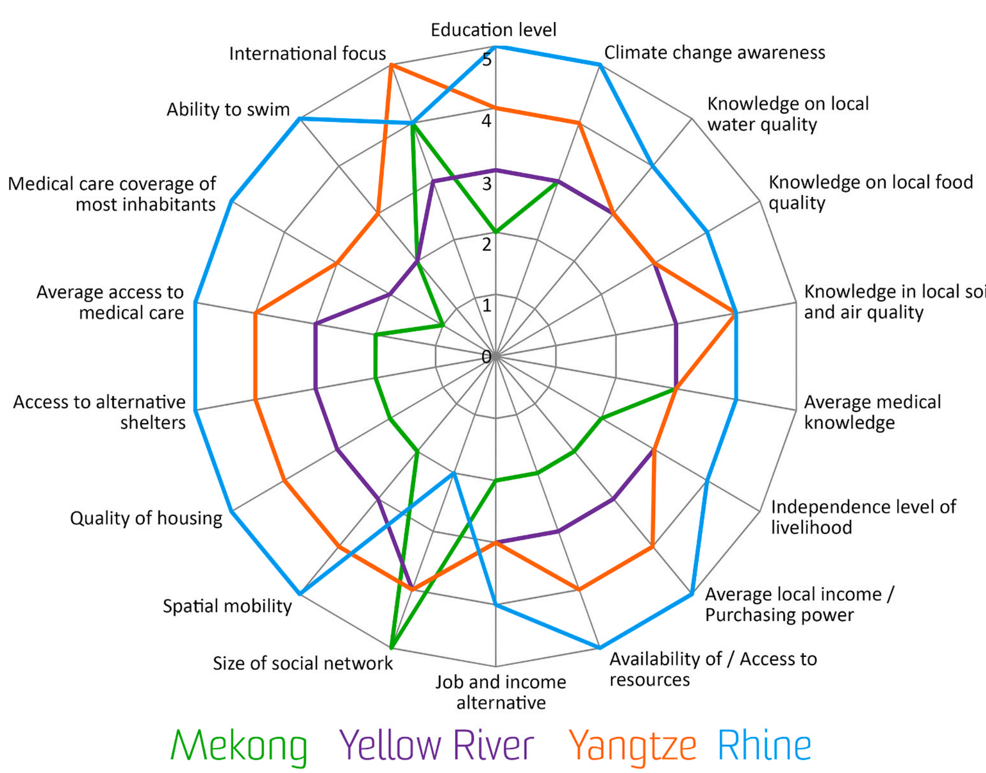


**Fig. 6.** Resilience profiles of the Mekong, Yellow, Yangtze, and Rhine River deltas (average inhabitant) based on parameters impacting a delta resident's resilience (resilience of the social system of the delta, which also impacts the ecologic and economic subsystems). Adaptation in deltas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

local ecosystems, and a sustainable, energy saving lifestyle. Political measures need to ensure that the first three strategies (educational, ecological, technological measures) are put into practice. Political measures include instituting decrees, rules, and laws, establishing bodies to conceive and monitor these regulations, and assuring law enforcement. At the same time, politicians and the economic sector can seek a healthy balance of technological, ecological, and educational measures. Ideally, no informal elite (hydrocracy) interest exists, and public decisions are made with a focus on a healthy equilibrium between socioeconomic development and the protection of natural resources (Benedikter, 2013; Kuenzer and Renaud, 2012).

Jointly, all involved authors identified adaptation measures that foster improved coping with internal and external threats and boost an inhabited river delta's resilience (Table 5). Each adaptation measure was then rated based on the degree to which it is being practiced or implemented in each river delta. A clear distinction was made between existing governmental plans or laws and enforced action.

The results of the expert rating of individual resilience components are presented in Fig. 7. Overall, it is apparent that the RHD is perceived as a well-managed delta, where the existence of emergency response plans, climate change adaptation plans, environmental laws, and health care plans are accompanied by on ground implementations and law enforcement. The technology driven adaptation measures (dykes, measurement networks, etc.) are also well developed; here the RHD is probably one of the best equipped and most strictly regulated river deltas worldwide, although the low elevation of much of the delta means that if levees breech, the impacts could be devastating. Improvements are still possible with ecological measures such as wetland protection, restoration or reforestation, and the extension of protected areas. What is striking for the MKD, YeRD and YaRD is that although emergency response plans, adaptation plans and bodies, and even environmental laws and regulations exist (the latter in China to a higher degree than in Vietnam), these deltas score much lower when their enforcement is evaluated. There is a clear divide between 'what the situation is on paper and what is done in the real world.' Although, for example, the MKD has been intensively researched in the past two decades, and development plans such as the Dutch Mekong Delta plan and disaster response strategies have been published (MARD, 2001), gaps and overlaps in responsibilities of land and water resources management, as well as competing and conflicting interests among the responsible ministries, such as the Ministry of Natural Resources and the Environment, MONRE, the Ministry of Agriculture and Rural Development, MARD, the Ministry of Construction, MOC, and others, has led to weak law enforcement (Waibel et al., 2012). This is aggravated by the influence of water hydrocracy networks (Benedikter, 2013; Waibel et al., 2012), family clans, and other informal networks with strong economic interests. A similar pattern exists for the YeRD, where pollution from the oil industry and other industries is extremely prominent (nearly all effluent is released into the landscape untreated (Jiang et al., 2011)) and law enforcement would lead to economic losses for the involved enterprises – enterprises that provide the main household income for the majority of families living in the delta.

### 5.5. Summary statistics

Fig. 8 provides a graphical summary of the comparative delta assessment presented in this paper. For each of the four categories assessed (i.e. external and internal threats, resilience and resilience boosting adaptation measures), a total assessment score was calculated by summing the rankings (i.e. from 0 to 5) over all 18 variables/processes considered. The maximum ranking that could be achieved in each category was 90. Even though information about areas of particular weakness or strength is lost by summing up the scores over individual variables, this approach facilitates the direct comparison of the overall state of each river delta. In addition to the total scores in each category (i.e. internal and external threats, resilience, and adaptation), an

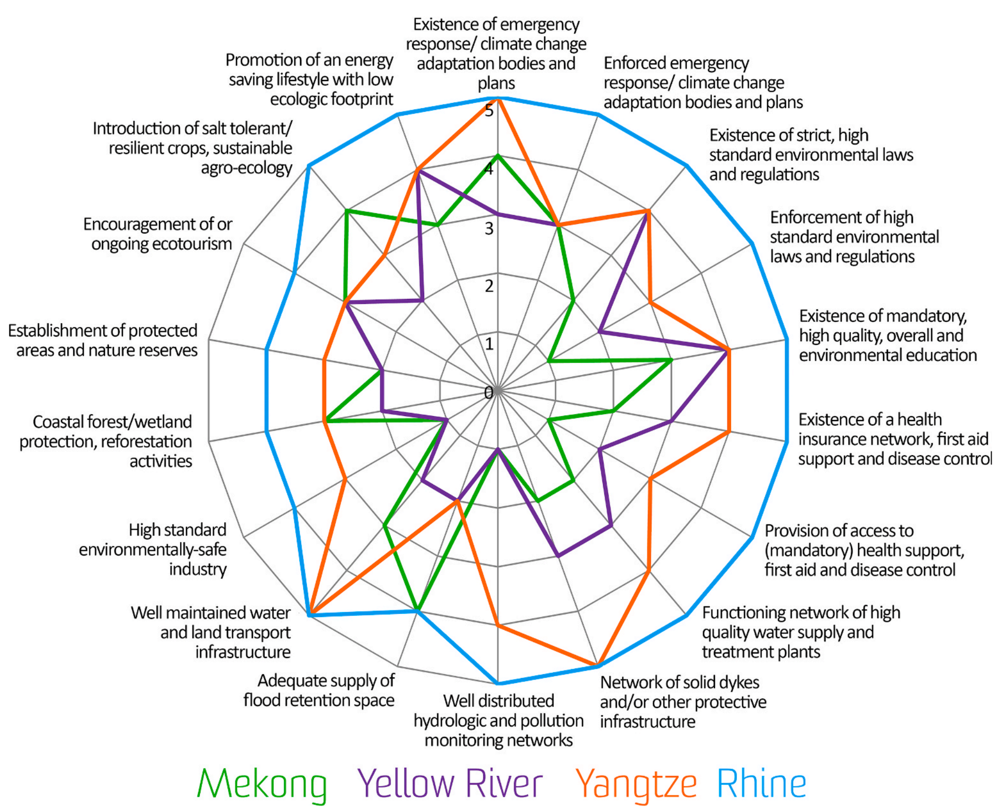


**Fig. 7.** Adaptation measures (and performance) boosting river delta resilience as rated for the Mekong, Yellow, Yangtze, and Rhine River deltas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

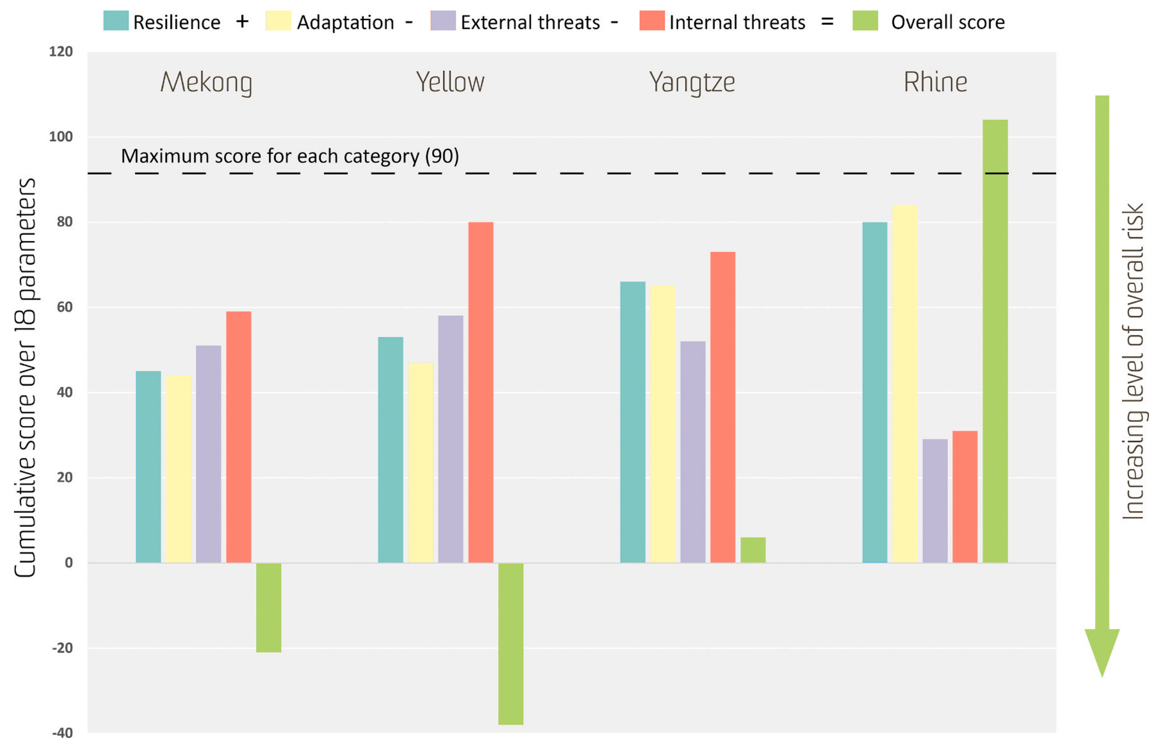


**Fig. 8.** Summary statistics of the external and internal threat, resilience and resilience boosting adaptation measures for the four deltas. Each bar represents the sum of ranks (out of 5) over each of the 18 variables in each category. The overall assessment score (light green) is a simple descriptive summary statistic, obtained by subtracting the cumulative ranks over the external and internal threats from the sum of the cumulative resilience and adaptation scores. This score should be interpreted as a summary statistic that facilitates the direct comparison of the river deltas, encompassing all the rankings provided in this study. Importantly, a high overall assessment score is representative of a safer situation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

arbitrary overall assessment score was then calculated by subtracting the external and internal threat scores from the sum of the resilience and adaptation scores. Importantly, since resilience and adaptation are treated as positives and threats as negatives in the applied formula, a high overall assessment score is representative of a ‘safer’ situation.

A number of interesting observations can be made based on the summary statistics for the four deltas. As expected, the RHD stands out with an overall assessment score of over 100, resulting from very high levels of resilience and adaptation on one hand, and comparatively low levels of external and internal threats. Interestingly, the lowest overall assessment score (i.e. least safe situation) was obtained for the YeRD, which has the third highest level of socio-economic development. Even though the YeRD scored higher than the MKD for resilience and adaptation, it also had the highest scores for internal (80) and external (58) threats, leading to an overall less safe situation. Offshore oil spills, allochthonous water and air pollution and upstream flow pulse changes stand out as particularly relevant external threats in the YeRD compared to the other deltas, while oil spill related pollution, wetland destruction, subsidence, air and water pollution stand out as relevant internal threats. This illustrates that the level of socio-economic development alone is not sufficient for explaining risk or resilience of river deltas. Sound management of natural resources, environmental regulations and enforcement of these regulations are critical for minimizing internal threats in river deltas but these measures are often undermined by hydrocracy interests and rapid industrial or agricultural development (Kuenzer et al., 2014a; Renaud and Kuenzer, 2012). This effect also becomes evident when looking at the YaRD, the second most socio-economically developed delta in this analysis. Here, the combined resilience and adaptation scores are 42 points higher than in the MKD but due to a substantially higher combined threat score (i.e. 125 compared to 110), the overall assessment score was only 27 points higher than for the MKD (the delta with the lowest level of socio-economic development). Importantly, the above comparison should be interpreted with care, given the simplistic nature of the summary statistics, which treated all 18 variables/processes in each assessment category as equally important. As such, Fig. 8 should be seen as a broad-brush overview of our comparative assessment, while Figs. 4–7 should be consulted for a detailed breakdown of the threat, resilience and adaptation levels and their individual contributors in each river delta.

## 6. Discussion

In this study, we attempted to profile threat, resilience, and adaptation states of four large and economically significant river deltas, considering processes of all three core subsystems (i.e. social, ecological, and economic). We achieved this through systematic interpretation of expert knowledge obtained via questioning of a diverse, but consistent mix of experts for each delta (i.e. decision makers, stakeholders, scientists, and other experts such as people working at NGOs). To maximize consistency in the profiles across the highly diverse river deltas, the assessments were based on a high level of joint expertise across the authors (i.e. for defining the 18 criteria for each assessment category) and subsequent systematic query and consolidation of expert knowledge (i.e. expert interviews). The joint expertise of the authors is founded on almost a decade of experience in all four deltas, with many of the authors having completed a multitude of interdisciplinary (i.e. climate science, hydrology, ecology, socio-economics) and multi-stakeholder (i.e. involving local populations, resource managers, industry, government and scientists) research, development and consulting projects. So, while the threat, resilience and adaptation profiles presented in this study are based on a qualitative approach, we believe that they are an accurate representation of the overall risk situation in each delta. The value of the presented profiles is supported by the fact that they generally show large differences across the four deltas (i.e. Figs. 4–7), and these differences are in general agreement with the level of socio-economic development, sound governance and sustainable management as well as delta specific threats. In the following paragraphs, we provide a discussion of the usefulness, implications and limitations of our assessment as well as the potential for alternative approaches and directions for future research.

Even though the list of processes and parameters used as the basis for our assessment is by no means exhaustive, it draws a clear picture of the overall situation in each delta. As such, our delta profiles enable a first pass assessment that can serve as a basis for prioritizing adaptation actions for boosting delta resilience or guide a more detailed and focused risk assessment. Overall, the RHD clearly stood out in terms of its comparatively low levels of internal and external threats, as well as very good levels of resilience and resilience boosting adaptation measures. This finding was not overly surprising, given the high level of socio-economic development in this region as well as sound governance in recent history and world-leading coastal engineering infrastructure. For the MKD, YeRD and YaRD, the internal and external threat profiles are not quite as distinguished, but still draw a clear picture of the dominant threats affecting each delta, with internal and external air and water pollution, sea level rise and subsidence requiring urgent actions (see Figs. 4 and 5). For the same deltas, the resilience profiles showed that there is a general lack of knowledge about climate change, the quality of local air, water and food resources as well as a lack of medical care coverage or the ability to swim.

Our adaptation profiles (Fig. 7) suggest that there is ample room for improvement in the overall and individual levels of resilience in the MKD, YRD, and even the densely populated YaRD. Strict law enforcement (which will evolve over time with overall improvements to government structures, state organs, and what is generally termed 'stateness') and high investments in clean technology (water treatment plants, water supply networks, renewed pipelines, chimney/exhaust filters, updated processing chains, etc. (Chen et al., 2013)) have the potential to increase the resilience of these deltas. In addition, our assessment shows that ecologic measures such as coastal reforestation, wetland restoration and protection, the establishment of nature reserves, and the development of the ecotourism sector are 'low hanging fruit' for boosting delta resilience. This is because many of the social and ecological parameters that contribute to a delta's overall resilience are interconnected. Healthy delta ecosystems such as mangrove forests or saltmarsh wetlands provide numerous ecosystem services such as improvements of water quality, supply of seafood and protection from storm surges, just to name a few (Maltby and Acreman, 2011; Newton et al., 2018). In return, this can improve a delta inhabitants' access to essential resources and protection from natural hazards. This is especially important for highly rural delta populations, which may rely strongly on subsistence fishing and farming or harvesting of other natural resources for supporting their livelihoods (Garschagen et al., 2012; Kuenzer, 2013). Recovering and maintaining healthy hydro-ecological systems throughout the delta through sound management of water (including upstream of the delta) and land resources and the establishment of nature reserves is therefore paramount for boosting resilience, in particular for rural delta populations. Notably, the resilience boosting adaptation profiles (Fig. 7) illustrate that also for the RHD, the there is room for improvement in the restoration and protection of coastal ecosystems, the establishment of protected areas and ecotourism.

Despite several existing studies that have undertaken a vulnerability or risk assessment in large river deltas or estuaries, the vast majority of these are focused either on the social, ecological or economic subsystem or a specific threat such as flooding and sea level rise (Ibáñez et al., 2014; Tessler et al., 2015; Wassermann et al., 2004) or land subsidence (Brown and Nicholls, 2015; Minderhoud et al., 2018; Törnqvist et al., 2010). While there is certainly a growing number of studies that treat deltas as social-ecological systems exposed to multiple threats (Anderson et al., 2019; Hagenlocher et al., 2018; Sebesvari et al., 2016; Szabo et al., 2016; Tessler et al., 2015), truly holistic assessments of delta resilience and comparison of resilience or risk profiles across deltas remain scarce. The continuing lack of holistic vulnerability assessments that jointly account for all dominant threats and delta subsystems has been discussed in detail in Wolters and Kuenzer (2015). While this paper aimed to profile resilience rather than vulnerability, the - to some degree - inverse nature of these two terms implies that holistic resilience studies are equally scarce. The highly complex and dynamic nature of delta environments, the lack of a clear and standardized definition of vulnerability and resilience as well as the high level of diversity in the methodological approaches taken by different authors or across different disciplines all pose difficulties for a quantitative whole-of-system assessment. Here, we partially overcame these difficulties by taking an expert knowledge approach rather than quantitative approach for profiling threats, resilience, and adaptation in each river delta.

While this approach allowed us to characterize the overall situation in each delta consistently and holistically, it is certainly subjected to several caveats. As with all qualitative assessments, the potential subjectivity or bias of different interviewees may skew the results. While we aimed to interview an equal mix of scientific experts, government representatives and practitioners for each delta, it is evident that each group was somewhat unique in respect to their overall and specific knowledge of the delta. Even though our expert surveys were structured and based on 18 indicators for each assessed element, the statistical representativeness of the chosen group of experts was not explicitly tested. There are now a number of systematic frameworks for quantifying system resilience with, for instance, a matrix based approach that has been exemplified for the Rockaway Peninsula, New York (Fox-Lent et al., 2015), or a tiered framework comparable to that commonly used in risk assessments (Linkov et al., 2018). The use of such a tested and published framework would have certainly added to the robustness of our assessment.

It should also be mentioned here that there has been a paradigm shift in the conceptual understanding of resilience in the academic literature over the last decade. Whereas traditionally, resilience was often interpreted as the direct counterpart of risk (i.e., high risk equals low resilience and vice versa), Linkov et al. (2014) suggest that the two concepts should not be used interchangeably, with resilience being a property of the system that unlike risk management, which is typically more event focused, includes a temporal component (i.e. the ongoing system management response following an adverse event). In this assessment, we used the concept of resilience more in the traditional sense, as this is still a common usage of the concept across the hydrological and coastal geosciences disciplines (e.g., Firley and Deupi, 2017; Thorne et al., 2018). In addition, due to the developing nature of some of the assessed river delta regions, where institutions are often weak, we focused on individual resilience in addition to institution-focused resilience, which would have been more appropriate in highly developed regions with strong institutions (Larkin et al., 2015).

The usefulness of a qualitative approach has previously been illustrated in Wolters et al. (2016), who undertook a comprehensive household survey to assess environmental awareness and vulnerability in the YeRD. Their study illustrates that low levels of education, income and correspondingly low awareness levels of global climate change and sea level rise are amongst the biggest factors contributing to the vulnerability of rural populations in the delta. These findings highlight one of the main advantages of a qualitative approach, namely that it can provide information, which is not readily captured in publicly available data sets or even data from government institutions or NGOs. The main alternative for a qualitative approach are quantitative assessments but, as discussed in Wolters and Kuenzer (2015), these are not always feasible. Most importantly, the quality, type and abundance of quantitative data is highly variable across different social, ecological or economical delta processes and threats, with data availability likely being heavily-biased towards economically significant resources or threats. This bias might be particularly dominant in developing and emerging countries, where datasets are often classified, lack quality control, or simply do not exist.

In recent times, more and more of the processes relevant for delta risk and resilience assessment are becoming quantifiable thanks to advances in data mining (social media, publicly available data, government agencies) and earth observation. Earth observation or satellite remote sensing can provide spatially explicit and unbiased data on many important natural (e.g., inundation, wetland and forest extent, shoreline accretion or erosion, subsidence, land use change) and socio-economic (e.g., urbanization, compliance with environmental regulations, industry expansion) processes, as well as their evolution over time. A comprehensive overview of the potential for Earth observation for quantifying various key features and processes across large river deltas and estuaries is provided in Kuenzer et al. (2019). Remaining challenges are the fact that the remote sensing scientists that derive end user products from raw satellite data do not necessarily 'speak the language' of other disciplines involved in delta risk assessment and it is often difficult for non-remote sensing experts to analyze or employ these potentially large spatio-temporal datasets. Future studies on delta vulnerability, risk or resilience should leverage recent advances in remote sensing and data mining for generating a truly unbiased and consistent data basis for the risk or resilience assessment.

## 7. Conclusion

Coastal river deltas are highly dynamic social-ecological systems that are often affected by a large number of natural or anthropogenic threats. As global hotspots of population and economic growth, deltas have moved into the focus of international research. However, the complexity of social-ecological delta systems still poses difficulties for assessing their resilience holistically, taking into account all relevant subsystems (social, ecological and economic). Here, we used an expert knowledge-based approach for generating assessments and comparisons of threat, resilience and adaptation levels of four large deltas with unique geographies and different levels of socio-economic development, namely the MKD, YaRD, YeRD and RHD. The following conclusions can be drawn from our comparative assessment.

- The lowest overall assessment score was obtained for the YeRD, followed by the MKD and YaRD respectively. Very high levels of internal and external pollution sources as well as exploitation and destruction of natural resources are responsible for the low overall scores in the YeRD and YaRD, despite their higher levels of socio-economic development. The highest overall score was obtained for the RHD.
- Resilience and resilience boosting measures are strongly linked to socio-economic development as well as sound governance and sustainable management of a delta region. Resilience and adaptation levels are highest for the RHD, followed by the YaRD and YeRD, while the MKD is faring the poorest. The threat profiles, on the other hand, are somewhat decoupled from socio-economic development. Although the RHD has significantly reduced internal and external threats profiles, the differences for the three Asian mega deltas were substantially less pronounced. The geographical setting and corresponding exposure to natural threats (i.e. sea level rise, floods, subsidence) as well as the geopolitical setting (i.e. multiple countries sharing a river catchment or delta) are important factors affecting the threat profiles in addition to socio-economic development.
- The resilience boosting adaptation measure profiles illustrate that there is significant opportunity for improvement in the MKD, YeRD, and YaRD. Strict law and policy enforcement, improvement of governmental structures and investments in water infrastructure and clean technology are needed in these deltas.
- Deltas should be treated as complex and interwoven social-ecological systems. Many of the social and ecological pillars of delta resilience are intrinsically connected and the recovery and maintenance of functioning hydro-ecological systems across deltas can be seen as one of the key measures for boosting resilience. Unfortunately, poor enforcement of environmental regulations, hydrocracy interests as well as ongoing expansion of agriculture, aquaculture and hydrocarbon extraction are currently still leading to decay, rather than improvement. Consequently, subsistence-based rural populations that already suffer from low levels of resilience continue to be adversely affected until a more sustainable management of delta ecosystems is implemented.
- Due to a lack of feasible alternatives, a qualitative approach was the most suitable method for performing a comparative assessment of resilience across the four river deltas. Quantitative approaches should be the method of choice whenever a consistent and unbiased data basis can be obtained. Considering the extreme differences in the availability and quality of data available for the four analyzed deltas, as well as the multitude of processes and subsystems considered, it was not possible to compile an unbiased and uniform database.
- Recent advances in Earth observation, access to a wealth of free and open data, and novel techniques of data mining are opening new possibilities for a more quantitative and holistic assessment of delta vulnerability or resilience. Especially Earth observation analyses can provide unbiased, spatially explicit, and repeated (i.e. time series) data on many of the processes that feed into a resilience or vulnerability assessment.

## Declaration of competing interest

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

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