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Sustainable deltas: livelihoods, ecosystem services, and policy implications

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Coastal river deltas are dynamic and highly fertile landforms at the intersection of terrestrial and marine environments. They are often densely populated due to the opportunities for livelihood generation they offer, in particular, through agriculture and aquaculture production, but also for economic development and trade (Kuenzer and Renaud 2012). At the same time, and largely because they offer so many opportunities for development, many river deltas globally are threatened both by environmental and anthropogenic processes (Syvitski et al. 2009; Tessler et al. 2015; Szabo et al. 2015a). Deltas and their river basins are naturally dynamic systems, but human interventions in situ, such as urbanization, groundwater and hydrocarbon extraction, agricultural intensification, and channel regulation, and ex situ, including increased upstream water withdrawals, diversion and sediment trapping, increasingly combine with coastal hazards, such as sea level rise, salinity intrusion, and hurricanes to threaten delta social–ecological systems (e.g., Renaud et al. 2013). In combination, such processes exacerbate livelihood losses and existing inequalities, precipitate migration streams and often create new pockets of poverty, especially in urban centers within delta regions (Martin et al. 2013).

The increasing threats to populated river deltas are well recognized, and various networks are addressing delta-specific issues, such as the Delta Alliance[1] and the recently launched International Delta Coalition,[2] to name just two. In 2011, Foufoula-Georgiou et al. (2011) called for an "International Year of Deltas" aiming to address a number of interlinked research questions to improve our scientific understanding of deltas as social–ecological systems (SES) and, thus, contribute to long-term sustainable development of these regions. In 2015, the idea of having an international initiative, Sustainable Deltas 2015, dedicated to deltas was endorsed by the International Council for Science.[3] The need for further research and increased standardization of research methodologies for delta environments was further acknowledged by Giosan et al. (2014:33) who called for a "science-based global strategy for protecting deltas". Furthermore, Hossain et al. (2016) highlighted the need for in-depth studies of complex ecosystem services in the context of socio-economic development at a regional level. Given the above and the various political milestones that were reached in 2015, including chronologically the Sendai Framework for Disaster Risk Reduction (UN 2015a), the Sustainable Development Goals (SDGs) (UN 2015b), and the Paris Agreement on climate change (UNFCCC 2015), there is an urgent need for addressing delta sustainability concerns, and science has an important role to play in this effort.

The recently endorsed SDGs create new opportunities for the understanding of development and sustainability in delta regions (Szabo et al. 2015b). The SDGs focus much more explicitely than the previous Millennium Development Goals on environmental sustainability, the impacts of climate change, the importance of ecosystems and

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[1] http://www.delta-alliance.org/.

[2] https://www.government.nl/latest/news/2016/05/10/minister-schultz-launches-international-delta-coalition.

[3] http://www.icsu.org/news-centre/news/top-news/icsu-endorsed-initiative-sustainable-deltas-2015-launches-in-rotterdam.

ecosystem services, sub-national differences and the need for disaggregated data, the latter perhaps opening a window of opportunity to collect more delta-specific information. Also, water and soil salinization, a concern in many delta environments and which has negative impacts on food security and, more broadly, households' livelihoods (Szabo et al. 2015b), have been at least partially accounted for through target 6a in the context of water harvesting, desalination, and water efficiency (UN 2016; Szabo et al. 2015a). Nonetheless, the environmental vulnerability, combined with rapidly changing demographic dynamics in many river deltas, including often high rates of out-migration (Szabo et al. 2015c), implies that an intensified effort will be required to ensure sustainable socio-economic development for delta populations. Therefore, despite increased global political and policy progress, multi- and inter-disciplinary research and multi-stakeholder engagement are and will continuously be critical to generate robust evidence for effective policy design (Brondizio et al. 2016).

In 2008, *Sustainability Science* published a series of papers under a Special Feature entitled "Global sea level rise and coastal vulnerability" (Harvey and Nicholls 2008). One of the featured papers identified large-scale engineering structures, such as dams, over-abstraction of underground resources, and water diversion schemes as often being more threatening to deltas' social–ecological systems than eustatic sea level rise (Syvitski 2008). This special issue of *Sustainability Science* builds on this, and other papers published since then on delta-related issues. It addresses the sustainability of deltas through various disciplinary angles and considers livelihoods, ecosystem services, vulnerabilities and risks, and the policy implications of some of these issues. Crucially, several of the papers include reports of studies carried out in recent years by multi-disciplinary teams of researchers who have together addressed various aspects of delta sustainability.

This special issue was developed as a contribution to the Sustainable Deltas 2015 initiative and draws on the work carried out within the BF-DELTAS project[4] "Catalyzing action toward sustainability of deltaic systems with an integrated modeling framework for risk assessment" which was granted by the Belmont Forum (BF) in 2013 (Foufoula-Georgiou et al. 2013) and is executed by a consortium of 22 research partners globally (see also Brondizio et al. 2016). The project allowed for a broad range of research teams covering different disciplines to work together and engage with stakeholders in various deltas. The BF-DELTAS project had five main objectives: (1) developing a theoretical framework for assessing delta vulnerability (Delta-SRES); (2) co-developing an open-access, science-based, integrative modeling framework called the Delta Risk Assessment and Decision Support (Delta-RADS); (3) consolidating and making readily available relevant data on bio-physical, social, and economic parameters (Delta-DAT); (4) developing Global Delta Vulnerability Indices that capture the current and projected physical–social–economic status of deltas around the world (Delta-GDVI); and (5) demonstrating the above-mentioned products in selected deltas (Delta-ACT). Although the project aimed at addressing sustainability issues of deltas globally, field-based research focused on three deltas: the Amazon River delta (ARD), the Ganges–Brahmaputra–Meghna delta (GBM), and the Mekong River delta (MRD).

Of the 12 papers in this special issue, seven are fully or partially stemming from the BF-DELTAS project (with a few having multiple sources of funding), the other papers being contributions obtained through various announcements made notably during the 2014 American Geophysical Union Fall Meeting and are from researchers not involved in the project. One paper covers deltas globally, three cover the three deltas studied in more details in the BF-DELTAS project, three focus on the ARD, two on the MRD, one on the GBM, one on the Huanghe River delta, and one on the Mississippi River delta.

Recognizing that delta sustainability is precluded by anthropogenic activities locally, at the river basin scale, and globally, Tessler et al. propose in this special issue a methodology for developing an empirical typology of anthropogenic change for deltas worldwide. Through a cluster analysis of 48 deltas, they identified groups of deltas facing similar sources and degrees of anthropogenic stress that influence relative sea level rise and contribute to the loss of coastal wetlands. Six globally quantified indicators were used to characterize anthropogenic stress: population density, reservoir volume sediment trapping, wetland disconnectivity, impervious surface area, groundwater depletion, and oil and gas extraction. This approach and resulting groupings could eventually lead to policies and delta management practices addressing the specific needs of deltas.

To unravel the complex socio-ecological factors affecting the sustainability of delta regions and design effective policy measures, it is critical to understand the demographic trends and prospects in these regions. This encompasses not only the trends in population growth (or decline), but also the analysis of the specific components of population change, i.e., fertility, mortality, and migration. This analysis is undertaken in the paper by Szabo et al. Using case studies of the ARD, GBM, and MRD, and a novel conceptual framework, the paper discusses the complex interrelationships between population and environment with a specific focus on deltaic systems.

[4] http://delta.umn.edu/.

Recommendations include designing specific policy measures in the context of aging populations and disproportionately high out-migration in some regions.

de Araujo Barbosa et al. investigate social–ecological systems of the ARD, GBM, and MRD through the analysis of time series of demographic, economic, health, climatic, food, and water data. A framework to investigate social and biogeophysical changes in the three deltas is proposed and is populated with indicators reflecting past and current states of provisioning and regulating ecosystem services, but also of physical drivers and elements of well being. Trends in many variables analyzed, such as rising population and GDP, fluctuating climate drivers, rising or fluctuating provisioning services, and declining or fluctuating regulating services are similar in the three deltas. Regional exceptions are noted in the ARD with, for example, a rise in temperature since the mid-1990s. None of the variables showed quasi-stationary patterns, indicating that the three deltas' social–ecological systems are in transient states. The authors highlight the fact that the sustainable development of the deltas will only be possible once local economic growth is decoupled from local resource use as the latter strains ecosystems which could reach, eventually, irreversible tipping points.

To provide critical quantitative information on the vulnerability of deltas facing multiple environmental hazards, Sebesvari et al. carried out a systematic review of indicators typically used in past vulnerability assessments in the ARD, GBM, and MRD. They present a vulnerability and risk assessment framework for delta SES along with the list of indicators used in past assessments categorized following the logic and elements of the framework. Through the review, they note that most vulnerability assessments in these deltas are typically carried out for single hazards and for only few components of SES. Also, there was a disparity in the types of indicators developed and used in past studies, with a majority of the 236 indicators compiled in the review addressing the social dimension of SES and much fewer characterizing the ecological component. The resulting indicator list provided through the review could serve as a "library" of indicators to be used more systematically in future studies.

This special issue features three distinct studies on the ARD region focusing on different aspects of vulnerability and adaptive capacities. First, Brondizio et al. introduce a comprehensive tool for the practical analysis of deltas as coupled SES. The first part of the framework can be used to define a delta SES, and the second part is a generalized strategy for the analysis of collective action problems in the chosen delta region. This framework is intended to support both comparative analysis as well as case studies as illustrated by their exemplar delta action problem based in the ARD.

Second, Vogt et al. offer new insights into the role and functions of local ecological knowledge (ILK) in mitigation and adaptation processes to changing flood patterns in the ARD. The paper examines how farmer–fishers use ILK to cope with challenges resulting from environmental and climate change, such as sea level rise and flooding. The results show that expert farmer–fishers use ILK to adapt to the impacts of extreme flood events at the landscape, community, and household levels and to manage agrobiodiversity, including forest resources, fisheries, and agriculture.

Finally, the paper by Mansur et al. assesses urban vulnerability in the Amazon delta and estuary by applying a multi-criterion index, which considers the three main dimensions of urban vulnerability in the regions, i.e., flood exposure, socio-economic sensitivity, and infrastructure. The results suggest that 60–90 % of urban populations experience moderate or high vulnerability and that vulnerability increases from city centers to peri-urban areas. The results yield critical policy implications for sustainability and urban planning in the AMD region.

Two papers address the sustainability of the Mekong delta. First, Thang Thi Xuan Nguyen and Woodroffe investigate relative vulnerability to sea level rise (SLR) in the Kien Giang coast, in the western part of the delta in Vietnam. Due to its geographical location, this region is likely to receive little sediment and be particularly vulnerable to SLR. They derived a composite vulnerability index for the region using the analytical hierarchical process method for multi-criteria decision making which was integrated in a geographic information system. The results showed that the coastal fringe is exposed to salinity, floods, and moderate loss of mangrove. Districts in coastal areas had moderate to high vulnerabilities to SLR. The paper also clearly identifies social and economic determinants of susceptibility and adaptive capacity in the region. The findings of this study are important in terms of informing targeted policy design, reducing inequalities, and, thus, contributing to sustainable development of the region.

Globally, the area of mangroves lost has been considerable during the past decades (see Duarte et al. 2013), in many cases through conversion to aquaculture, leading to the loss of many ecosystem services (van Wesenbeeck et al. 2015). In this special issue, Warner et al. focus on one of these ecosystem services, namely carbon sequestration in the MRD, offering multi- and inter-disciplinary perspectives of mangrove conservation and restoration. The research is indeed not limited to the amount of carbon that can be sequestered by mangroves in the MRD but also considers (1) the linkages between mangrove ecosystems and livelihoods, including, e.g., economic incentives and community ownership and engagement, (2) legislation, and (3) financial issues related to mangrove management. The carbon sequestration potential of mangroves is significant and can play an important role in climate change mitigation. Warner et al. propose directions to address the social, economic, political, legal, and scientific challenges linked to mangrove conservation and restoration to tap into this potential.

Ayeb-Karlsson et al. present findings on livelihood resilience in seven study sites across the Ganges–Brahmaputra delta in Bangladesh from a qualitative investigation into how people build resilience against environmental stresses, such as cyclones, floods, riverbank erosion, and drought. In this work, the voices of people from the delta are clearly heard, arising directly from Ayeb-Karlsson et al.'s methodologically novel personal livelihood history interviews. The findings show how environmental stress, shocks, and disturbances affect people's livelihood resilience and why adaptation measures can be unsuccessful. People manage to adapt to environmental stresses by modifying their agricultural practices, switching to alternative livelihoods, or using migration as an adaptive strategy. They argue successfully that 'people-centred' research and findings are important to future policy and adaptation planning.

Two other deltas are addressed in the special issue. First Bao and Gao provide a detailed analysis of environmental characteristics and land use pattern changes of the Old Huanghe River delta, eastern China, during the sixteenth to twentieth centuries. The paper uses multi-disciplinary methods to assess the relationship between ecosystem changes and human activities and shows that in the sixteenth to nineteenth centuries, the government held a significant proportion of ecological resources. However, later, this pattern became unsustainable, and government-controlled activities were largely replaced by farming activities of local residents. The authors guard against monopolistic policies, which could harm the development of the delta region and prevent interactions between social and ecological systems.

Last, Twilley et al. investigate the SES of the Mississippi River Delta Plain (MRDP), focusing on the impacts of reduced sediment supply through river flooding on landward migration of the 50 % Land: Water isopleths, changes in types of vegetation, and on changes in wave power. They compute land to water ratios historically along the coast of the Atchafalaya and Terrebonne basins to estimate flood risk linked to changes in sediment supply, and discuss the social and economic consequences of decreasing land to water ratios in the MRDP.

The papers in this special issue address the multiple physical, ecological, social, political, and policy dimensions of deltas' sustainability, in several cases addressing two or more of these dimensions within the same study. Given the complexity of deltas' SES and multiple interactions and feedback loops between the components of these SES at multiple spatial scale, more multi- and interdisciplinary policy-relevant research programmes are needed with international teams of scientists, practitioners, members of regional organizations, representatives of civil society, and policymakers working closely together with populations locally and at river basins scales. As highlighted by Brondizio et al. (2016), this will require innovative funding mechanisms. Such mechanisms should aim to support international partnerships with equitable funding streams for all involved and for longer periods of time than traditional project cycles of 3–4 years. This might be the only realistic way forward for developing science-based policy-relevant recommendations to authorities involved in governing deltas and to ensure that the SDGs are achieved by 2030 in delta regions globally.

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