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A vision for a coordinated international effort on delta sustainability

EFI FOUFOULA-GEORGIOU

Department of Civil Engineering and National Center for Earth-surface Dynamics, University of Minnesota, USA
efi@umn.edu

Abstract Deltas are economic and environmental hotspots, food baskets for many nations, home to a large part of the world population, and hosts of exceptional biodiversity and rich ecosystems. Deltas, being at the land–water interface, are international, regional, and local transport hubs, thus providing the basis for intense economic activities. Yet, deltas are disappearing and deteriorating at an alarming rate as "victims" of human actions (e.g. water and sediment reduction due to upstream basin development), climatic impacts (e.g. sea level rise and flooding from rivers and intense tropical storms), and local exploration (e.g. sand or aggregates, groundwater and hydrocarbon extraction). Although many efforts exist on individual deltas around the world, a comprehensive global delta sustainability initiative that promotes awareness, science integration, data and knowledge sharing, and development of decision support tools for an effective dialogue between scientists, managers and policy makers is lacking. Recently, the international scientific community proposed to establish the International Year of Deltas (IYD) to serve as the beginning of such a Global Delta Sustainability Initiative. The IYD was proposed as a year to: (1) increase awareness and attention to the value and vulnerability of deltas worldwide; (2) promote and enhance international and regional cooperation at the scientific, policy, and stakeholder level; and (3) serve as a launching pad for a 10-year committed effort to understand deltas as complex socio-ecological systems and ensure preparedness in protecting and restoring them in a rapidly changing environment. This paper articulates the vision for such an initiative as developed by a large number of international experts (see contributing authors) and pleads for a comprehensive and coordinated effort that spans continents and environments to demonstrate that indeed these "hot spots of vulnerability and change" can become again "seedbeds of sustainability and resilience."

Key words delta sustainability

Contributing authors I. Overeem (Univ. of Colorado, USA); Y. Saito (Geological Survey of Japan, Japan); S. Dech and C. Kuenzer (University of Wuerzburg, Germany), S. Goodbred (Vanderbilt University, USA); I. Harrison (Intern. Union for the Conservation of Nature, USA); E. Anthony (Aix-Marseille University, France); E. Brondizio (Indiana University, USA); J. Hutton (United Nations Univ., UK); R. Nicholls, Z. Matthews, J. Dearing, A. Lazar and A. Baschieri (Univ. of Southampton, UK); A. Newton (Norwegian Inst. for Air Research, Norway); R. Ramachandran (Anna Univ., India); F. Renaud and Z. Sebesvari (United Nations Univ., Germany); C. Vorosmarty and Z. Tessler (City College of New York, USA); S. Costa (University of Vale do Paraíba, Brazil), K. M. Ahmed (Univ. of Dhaka, Bangladesh); M. M. Rahman (Bangladesh Univ. of Engr. and Technology, Bangladesh); G. Lintern (Natural Resources Canada, Canada); P. Van Cappellen and H. Durr (University of Waterloo, Canada), S. Gao (Nanjing Univ. China), M. Marchand and T. Bucx (Deltares, Netherlands); V. L. Nguyen (Vietnam Academy of Science and Technology, Vietnam); M. Goichot (World Wide Fund for Nature – Greater Mekong, Vietnam); and C. Paola, D. Mohrig and R. Twilley (National Center for Earth surface Dynamics, USA).

WHY DELTAS FOR A GLOBAL SUSTAINABILITY INITIATIVE?

Deltas are dynamic landforms at the land–water boundary, involving intricate mazes of rivers and small waterways, wetlands, estuaries and coastal barrier islands. They are home to over half a billion people – over 250 million people living in the three deltas of the Ganges-Brahmaputra-Meghna, Mekong and Nile rivers alone. Deltas are also home to biodiverse and rich ecosystems, such as mangroves, reedlands and marshes. They are economic hotspots, supporting much of the world's fisheries, forest products, and extensive agriculture, as well as significant growing cities and ports/harbours. Yet, worldwide delta systems are under dramatic threat from sea-level rise, cyclones, river flooding, storm surges, rapid urbanization, agricultural over-use and pollution, salinization, sediment starvation, coastal erosion, and natural and man-made subsidence.

Marine deltas are susceptible to sea-level rise, with alarming assessments that the surface area vulnerable to flooding could increase by 50%, including in many megacities, in the 21st century (see Fig. 1). However, delta fragility is not a simple story of slowly encroaching seas. It is a complex balance between constructive and destructive forces. Every delta is built by sediment distributed by river and coastal processes. Wetlands help by efficiently trapping sediment and they naturally protect against erosion. Humans impact the sediment fluxes enormously. On a global

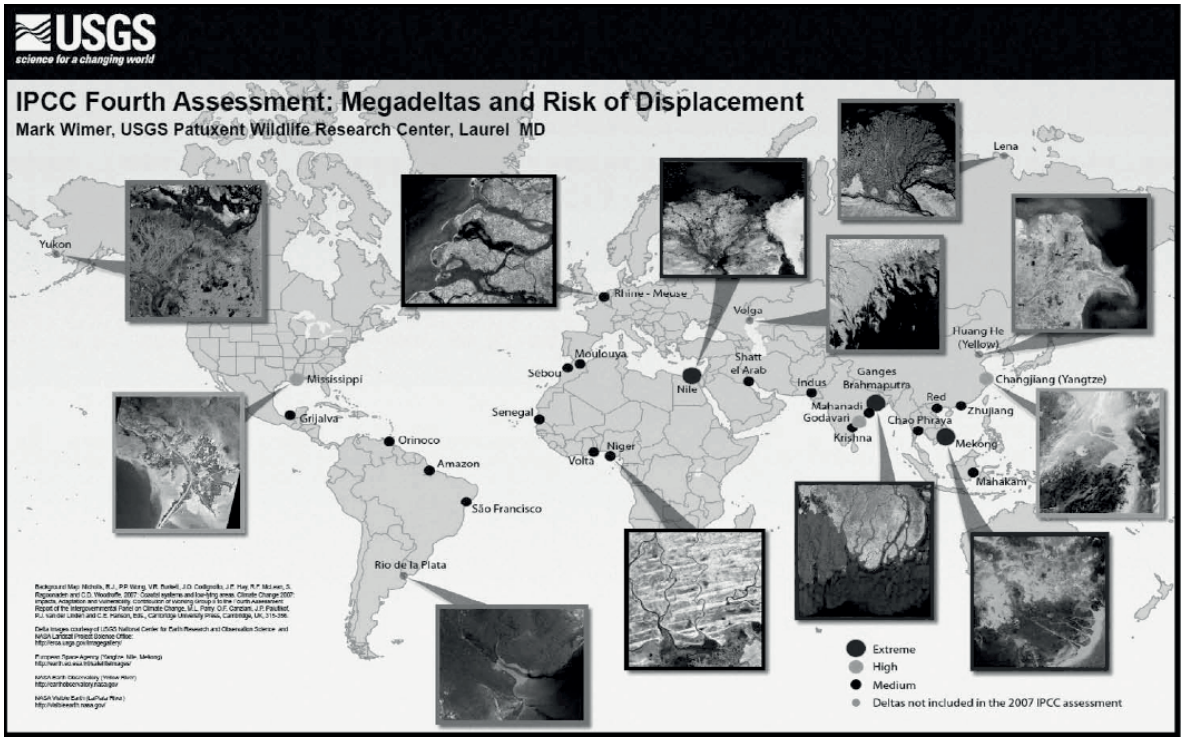

Fig. 1 Megadeltas around the world were identified in the 4th IPCC report as one of the most vulnerable environments threatened by climate and human-induced changes.

scale, >40% of river discharge and 26% of sediment are being intercepted by large reservoirs, which were built to regulate flow, manage water for irrigation and produce electricity (Vorosmarty *et al.*, 2004). Sand mining for aggregates, which are in urgent demand in developing countries, also accelerates erosion. Another widespread destructive force is subsidence, as for example a net elevation loss of several cm/year in the Chao Phraya delta on which Bangkok rests. Some deltas also undergo devastating flooding and destruction due to tropical cyclones; for example, cyclones in Asia since 1970 have caused over 500 000 fatalities.

The implications of deteriorating deltas cannot be overstated. To design sustainable delta systems, in which the regenerated land surface can balance relative sea-level rise, plant productivity can remain steady, and the output of economic goods and services can exceed the cost of engineering investments and government subsidies, local policy makers and managers require sophisticated science-based new assessment tools. This paper articulates a vision, co-developed by several leading scientists from the international community (see list of contributing authors), for a global partnership to save deltas around the world. The partnership will be a contract between academic institutions (experts from the physical and social sciences, economics, health/demographics, management and policy), local stakeholders and capacity building leaders from research institutes, government agencies, and non-profit organizations to make delta sustainability a top priority and demonstrate that indeed it is possible to use science and policy to "turn vulnerability to resilience." If this cannot be demonstrated in these highly localized threatened systems, how can we hope to demonstrate it in the entire coastal zone, and in the ultimate challenge of ensuring environmental sustainability and providing food and clean water for all, i.e. achieving the United Nations Millennium Development Goals (http://www.un.org/millenniumgoals)?

Coastal sustainability has been identified as a research focus and funding priority in many countries around the world. This has also been articulated by several international scientific organizations such as, for example, the International Council for Scientific Unions (ICSU) which has pleaded for global scientific partnerships "to deliver knowledge needed for action to mitigate

Fig. 2 Ten reasons why deltas are perfect showcases for a coordinated Global Delta Sustainability Initiative transcending research, education, management and policy.

and adapt to detrimental environmental change and extreme hazardous events" (cf. ICSU, 2010). Within the broader coastal environment, deltaic systems are focused "hot spots" which can serve as a showcase for the international community (see Fig. 2) to demonstrate how integrated science, management, and policy can transform deltas from "hot spots of change and vulnerability" to "seedbeds of sustainability and resilience".

The need for a Global Delta Sustainability Initiative has been voiced by the international community which called for the establishment of the International Year of Deltas (IYDs), as a year to launch such an initiative (Foufoula-Georgiou *et al.*, 2011). The IYDs effort has been endorsed by several international scientific bodies (see www.iyds-2013.org) and has been proposed to serve as a springboard for awareness and a call to arms for global coordination of science and policy for delta sustainability over the next decade. Also the IPCC underlines the urgent need to address challenges in coastal areas vulnerable to sea level rise. Global delta networks, such as the Delta Alliance, World Estuary Alliance or WWF's World Ecoregion Initiative all underline the existing research gaps in river Deltas of our world. It is the right time to solidify these disparate efforts by delivering the science, modelling frameworks, databases and implementation that will bring delta scientists and stakeholders together to make a difference in "saving the world deltas."

A FRAMEWORK FOR GLOBAL COOPERATION ON DELTA SUSTAINABILITY

The challenges faced by deltas around the world are many and vary depending on the specific stressors, the socio-ecological setting of the delta, and its response to each of those stressors (see Fig. 3). However, in most deltas there are some central major questions that lie at the heart of developing a framework for their sustainability. Such questions include: (1) How do climate change, pressure on resources and engineering/infrastructure development make people, biodiversity and ecosystems vulnerable? (2) How is this vulnerability to be measured? (3) How do delta areas absorb extreme events? What are the hydrological and ecological thresholds underlying the integrity of a delta region? (4) What are the relevant local and regional biophysical and social

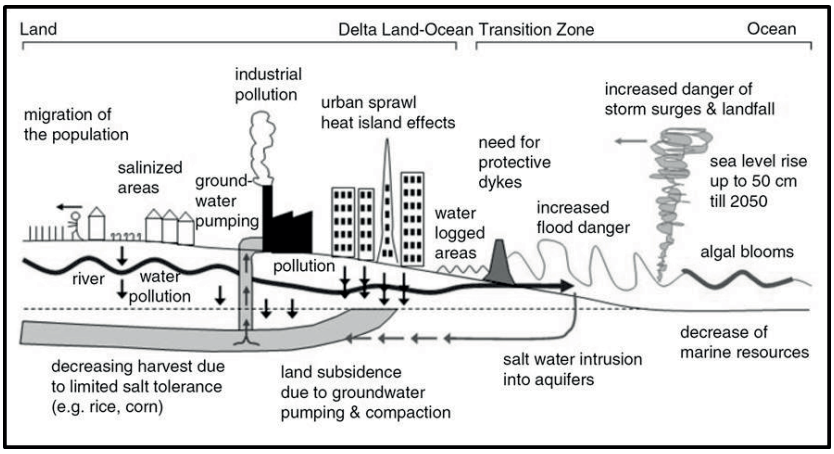

Fig. 3 Sketch of the most pressing challenges in delta areas globally (reproduced from Kuenzer & Renaud, 2012).

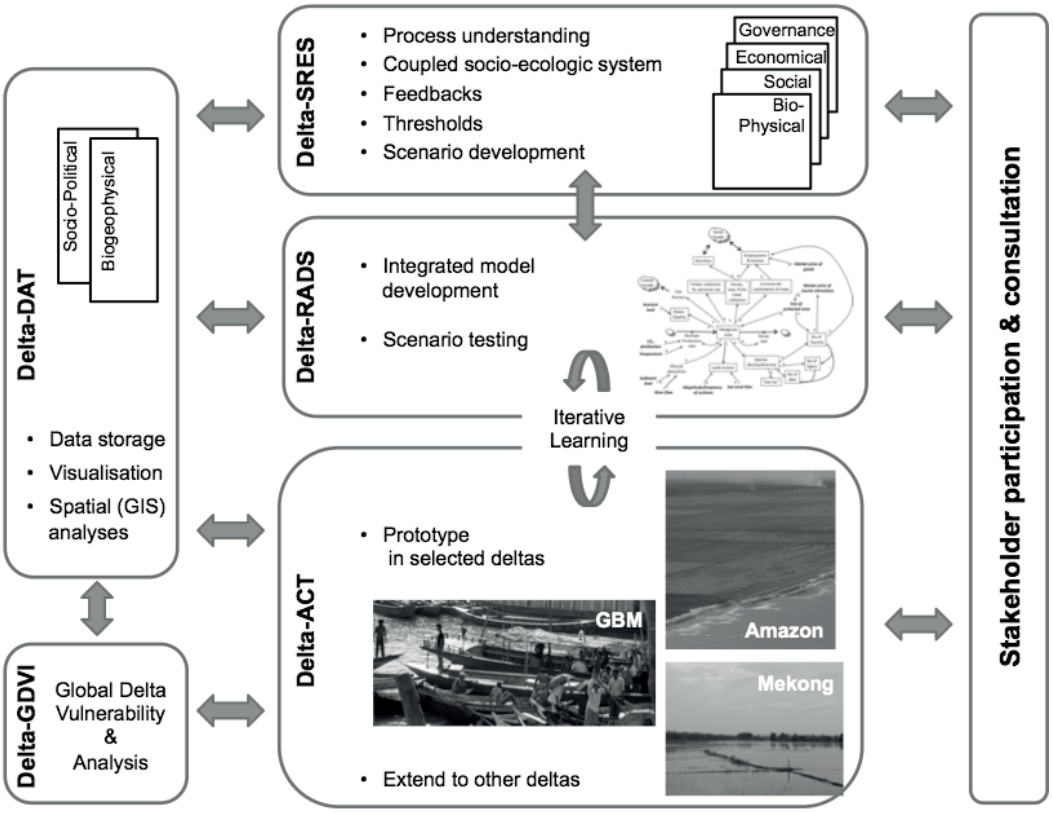

Fig. 4 Key components of a Global Delta Sustainability Initiative emphasizing the need for integrated research on deltas as coupled socio-ecological systems undergoing change (Delta-SRES), a global delta data depository (Delta-DAT), a suite of open access delta risk assessment and decision support modelling tools (Delta-RADS), and the coordinated demonstration of these activities in deltas around the world (Delta-ACT).

stressors for a particular delta system, how do these interact, and how do they vary spatially and over time? (5) How can regional delta sustainability be balanced with economic growth? and (6) How can one reduce future risk while attaining sustainable development?

The rationale behind the proposed Global Delta Sustainability Initiative is that of sharing scientific knowledge, data, and management and policy practices to accelerate actionable research and enable sustainable solutions. We maintain that a comprehensive decision-support modelling framework for deltaic regions that can be used to answer the above critical questions, does not

exist to date, and a platform for sharing knowledge on delta science, management, and policy is presently lacking. Every delta has its own unique story but critical knowledge can result by comparison and contrast and by synthesizing lessons learned: a delta subject to a devastating storm now can provide critical information for another delta which is certain to suffer a similar storm in the future; a heavily exploited delta now can form a prototype for another delta experiencing a similar path of exploration.

The goal of the proposed Global Delta Sustainability Initiative is: (1) to integrate the scientific knowledge on sustainability science of deltas as critical coupled socio-ecological systems undergoing change, (2) to develop and deliver a science-based delta sustainability framework for risk assessment and decision support, (3) to build an international repository of integrated data sets on deltas including physical, social and economic data, and (4) to implement and demonstrate the developed modelling and decision support framework in selected deltas of the world in partnership with local stakeholders, and open the door for global use and adoption.

The elements of the proposed Global Delta Sustainability Initiative are shown in Fig. 4 and discussed below.

Sustainability science of deltas as coupled socio-ecological systems (Delta-SRES)

Delta environments are complex systems integrating multiple nested spatial and temporal scales, and are subject to multiple drivers of change. While links between the environment, ecosystem services, and human wellbeing are widely asserted (Cinner *et al.* 2009; Vo *et al.*, 2012), these relationships are poorly understood in deltaic environments, despite the fact that they form the pillars of any sustainability initiative. A comprehensive science initiative on delta dynamics must integrate across three broad but strongly coupled themes: *ecogeomorphology, climate impacts, and human influence on deltas*. Having the analytical tools that examine these interactions across the different sectors of a delta and their implication for the ultimate vulnerability of the system as a whole is an area in which focused research is still required.

Major research questions that define the unique challenges that delta regions pose and highlight the need for the scientific community to synthesize and integrate our current knowledge base are: (1) How do the dynamics of a delta, including its main processes, reservoirs, and feedback loops, steer the system toward a particular equilibrium state? (2) How are these dynamics affected by human intervention and ongoing environmental change, especially with regard to maintaining a sustainable subaerial delta plain for human occupation? (3) What are the demographic and urban trajectories in delta regions with respect to population change, rates of poverty, and indicators of human well-being? and (4) What types of governance arrangements may help to facilitate and/or limit solutions to intricate multi-scalar problems of management, protection, and mitigation in delta regions?

Development of a delta risk assessment and decision support framework (Delta-RADS)

Modelling is the essential tool for understanding complex systems such as deltas, and for translating observations and scientific knowledge into predictive outcomes for management, policy, and scenario building. A pathway to delta sustainability requires a modelling system which: (1) encapsulates the spatial/temporal dependencies of the bio-physical environment and social dynamics of a delta, (2) is open access and runnable on personal computers, and (3) is credible to stakeholders and the decision-making process.

Although several elements of a delta modelling framework exist, they are scattered and lack the necessary integration into a coherent whole and an end-to-end decision support toolbox. These scattered elements include: hydrologic and sediment transport models, precipitation analysis of satellite data typically the only source of information for these coastal systems, river and estuary hydrodynamic models, biological and ecological models for the land–water interface, ocean models, socio-economic analysis frameworks, and small to large scale models of water–land–biota interactions. Modelling gaps are plenty and include the incompatibility between the scales at which data are available (from spatial average precipitation, to county level census data, to plot

scale land use), scales at which processes operate (from micro-scale for biology to larger scale for sediment and land–ocean interactions), and model grid scale needed for computational efficiency; parameter estimation from limited data; and probabilistic modelling using ensembles for quantification of risk and uncertainty.

Such an integrated modelling framework will be able to capture the effects of a dynamic range of drivers (climate, subsidence, demographic trends, economic development) on the natural, socio-economic and infrastructure resources of the delta. As such, it will enable studies to evaluate trade-offs and guide governance and management responses in terms of ecosystem restoration, adaptation of land and water use, land reclamation, flood preparedness, wetland use, and agricultural practices, to name a few.

Delta international data repository (Delta-DAT)

Although relevant datasets for regional delta studies are available in many forms, e.g. remote-sensing, topography, land use, ecosystem services, flood extent, sediment loads, climatology, historical storms, socio-economics, and management governance, among others, they are widely dispersed and thus provide limited utility for researchers and end-users. A Global Delta Sustainability Initiative requires a major effort to compile and hold observational and modelling data at a range of spatial scales, from global to sub-delta, and temporal scales. Specific holdings should include precipitation data from ground and remote sensors, topography, land cover and land-use data, habitat maps, flood situation assessment and coastline changes, and a diverse set of other geospatial data that jointly define the geophysical, biological, economic, and social contexts of the world's deltas. The database should include an assembly of comparative datasets for the past several decades that coincide with remote sensing data, especially based on >30 years of Landsat and NOAA-AVHRR imagery.

The deltas database should also include data from comparative global databases on socio-demographic and economic data; most of these data are available at the municipal level in national government census reports and data gateways and need integration and common platforms. Such a comprehensive database for deltas must be created now, and not in 10 years time, to guide sustainable development. Also, to make this database accessible to the international community, it is imperative that an IT backbone is also developed using the latest advancements in Earth system data processing and management such that it can link data providers to users through automated processing, data mining, serving, and archiving.

Development of global delta vulnerability indices (Delta-GDVI)

Globally, several risk, resilience and/or vulnerability indices have already been developed with different spatial resolutions (e.g. Turner *et al.*, 2003; Bucx *et al.* 2010; Birkmann *et al.* 2012). However, no comprehensive "vulnerability profile assessment metrics" currently exist that are at high spatial resolution and are spatially explicit enough to capture the profound spatial variability existing in delta systems, critically affecting the ability for successful local decision-making. To be of particular use to policy-makers, vulnerability metrics need to be developed based on indicators that are quantifiable at the sub-regional scale and transferable in different delta contexts. Policy factors which are critical in shaping future development of various delta environments, but also differ among various governance regimes, are often ignored in assessing delta vulnerability and need to be incorporated in vulnerability metrics. Emphasis also needs to be placed on capturing in vulnerability analysis the interface between ecosystems and social systems through understanding and quantifying delta ecosystem services and how these can be altered by external (e.g. environmental hazards) and internal factors (e.g. induced by policy decisions).

Regional implementation case studies (Deltas-ACT)

Every delta is unique with its own stressors and constraints and its own vulnerabilities. As such, a general fitting-all modelling and decision-support framework does not exist and is not promoted

BOX 1: UNIQUE DELTA STORIES PLEAD FOR A UNIFIED FRAMEWORK AND GLOBAL ACTION

The Ganges-Brahmaputra-Meghna Delta (GBMD):

The GBM Delta is one of the world's largest (~100 000 km^2) and most dynamic deltas draining land in Bangladesh, Bhutan, China, India and Nepal. The delta covers most of Bangladesh and part of West Bengal, India, with many of the 147 million people (in 2000) living in the delta under extreme poverty and facing multiple challenges. The population is expected to increase by 28% by 2015 (Overeem & Syvitski, 2009). Already 30% of Bangladesh is within 5 m of sea level, experiencing tidal water movement 100 km inland during the dry season (Allison, 1998), and relative sea-level rise that exceeds global-mean sea-level rise, demonstrating subsidence. Together these factors make the GBM delta one of the most vulnerable coastal regions in the 21st century (Nicholls & Goodbred, 2005).

Ensemble CCSM experiments predict 11% higher rainfall during the Asian monsoon (Meehl & Washington, 1993; May, 2003; IPCC, 2007), which would result in a larger sediment supply to the GBM delta in the future. In contrast, the proposed construction of numerous mega dams and major diversions upstream in India and China threaten sediment starvation to the sinking delta plain (Syvitski *et al.*, 2009), as well as reduced water availability in the dry season, which is already a serious problem. Reduced river flows and intensive shrimp farming cause severe saltwater intrusion in the coastal fringe degrading the ecosystem, and ultimately making the land uninhabitable.

The Mekong River Delta (MRD):

The MRD is considered to be the world's third largest delta (with an area of 93 781 km^2 and population of 17 million), is one of Asia's main food baskets, and is second only to the Amazon in terms of fish biodiversity (WWF, 2012). The major challenges in the MRD can be attributed to socio-economic transformation and urbanisation processes leading to the degradation of the last natural forest and wetland areas, accompanied by increasing water pollution (Kuenzer & Renaud, 2012). The MRD is now undergoing large-scale erosion, especially in the muddy mangrove-rich western part (Vo *et al.*, 2012), increasing its vulnerability under projected sea-level rise and impacting future food security (Leinenkugel *et al.*, 2011; Gebhardt *et al.*, 2012; Kuenzer & Knauer, 2013). Other activities include large-scale sand mining in the river and delta reaches, mangrove removal for shrimp farms, dikes and embankments to protect shrimp farms from flooding, and future large-scale hydropower development upstream (Kuenzer *et al.*, 2012).

The fact that the Mekong River catchment is shared among six countries (China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam) is a potential source of conflict in harnessing the resources of the basin, especially hydropower development (Grumbine & Xu, 2012; Grumbine *et al.*, 2012). Hydropower needs are expected to rise 7% a year over the next 20 years and plans afoot will, if implemented, exhaust the river's hydropower-generating capacity (Mekong River Commission, 2010), leading to a seven-fold increase in the reservoir sediment trapping efficiency (Kummu *et al.*, 2010) with adverse effects on fisheries (Ziv *et al.*, 2012) and coastal erosion (Le *et al.*, 2007; Xue *et al.*, 2011; Wang *et al.*, 2011; Räsänen *et al.*, 2012).

The Amazon River Delta (ARD):

The Amazon River is the world's largest, contributing 20% (175 000 m^3/s) of the total global river discharge to the oceans and discharging the highest total sediment load (Martinez *et al.*, 2009; Wittmann *et al.*, 2011). The delta includes vast estuarine wetlands at the mouth of the river and sustains equally vast muddy wetlands >1500 km north along the coast, influencing the coastal economies of Brazil, French Guiana, Surinam, Guyana and Venezuela (Anthony *et al.*, 2010). However, like the GBMD and MRD, the conversion of mangrove forests to shrimp farms in the ARD and north along the coast are an emerging environmental challenge (Anthony & Gratiot, 2012a; 2012b; Rovai *et al.*, 2012).

In terms of other environmental challenges that are typically associated with delta systems, the ARD is often classified as 'low risk' because of its limited damming and water/oil extraction (e.g. Syvitski *et al.*, 2009). However, deforestation proceeds at a rapid pace, and population, economy, and infrastructure in Amazonia are growing quickly. Furthermore, the projected construction of dams, ports and aqueducts as part of the ongoing regional integration development policies is expected to impact water and sediment flow from large tributaries such as the Madeira and Xingu rivers to the ARD (GeoAmazonia, 2009). The Amazonian basin is also currently under a massive plan for infrastructure transformation including continental cross-national highways, river and sea-ports, and a sequence of dams combining transportation river-ways and hydro-electrical plants. Ultimately, like all deltas, the ARD faces multiple, imminent environmental threats.

here. However, a fundamental element of delta sustainability is similar for all deltas: that of understanding cause and effect, small-to-large scale propagation of perturbations, physical to social to economic interconnections, and the fact that putting all these elements together in a single modelling framework will allow scenario building, development of system insight, and evaluation of alternative management options. We present in Box 1 the story of three distinct deltas, which highlight the differences but also similarities among these complex systems and speaks for the need to learn from comparison and contrast: what happens at one delta today might be the story of another delta's future.

THE TIME IS NOW FOR A GLOBAL DELTA SUSTAINABILITY INITIATIVE

Deltaic systems span an impressive array of Earth-science, biological, social, and economic domains, and epitomize the need for a trans-disciplinary approach to understand and manage them. Deltas have been identified as one of the four critical zones for pressing international and actionable research on global environmental change (the other three critical zones are: the arctic, tropical forests, and cities) (http://www.icsu.org/future-earth/who/transition-team). A lot has been written about deltas, several delta meetings take place each year, a lot of projects are funded by federal and private agencies around the world, a lot of change is happening already and much more is anticipated. The proposed Global Deltas Initiative calls for a comprehensive international effort to put the pieces together, to create awareness, to create a platform for learning from comparison and contrast, to exchange data and scientific knowledge, to bring managers and scientists together towards a common goal to save each and every delta around the world.

The time is ripe for a Global Delta Sustainability initiative. Several countries are investing in sustainability research, the coastal zone is a central focus of such activities, the research community is ready to make its science actionable, and the political will for global cooperation is at its highest (2013 has been declared as the International Year of Water Cooperation). The proposed International Year on Deltas (IYD) has been met with astonishing support by researchers, stakeholders and policy makers around the globe and speaks for the converging forces to make a difference. The community is called to action to seek this opportunity and move forward with determination and resolution to make the Global Delta Sustainability Initiative a reality.

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