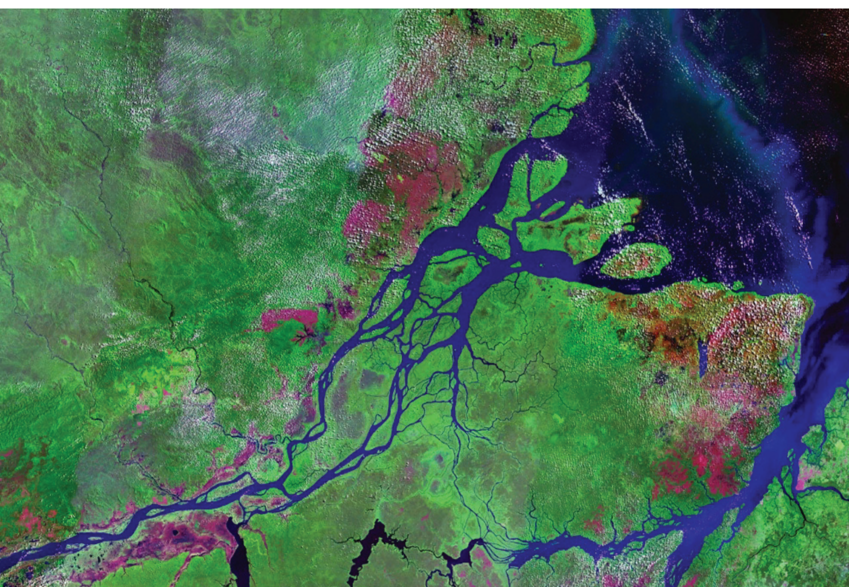


DELTAS: Catalyzing Action Towards Sustainability of Deltaic Systems with an Integrated Modeling Framework for Risk Assessment

DELTAS
SUSTAINABLE DELTAS 2015




BELMONT FORUM

Belmont Forum-G8 Collaborative Research:

BF-DELTAS:

Catalyzing action towards sustainability of deltaic systems with an integrated modeling framework for risk assessment

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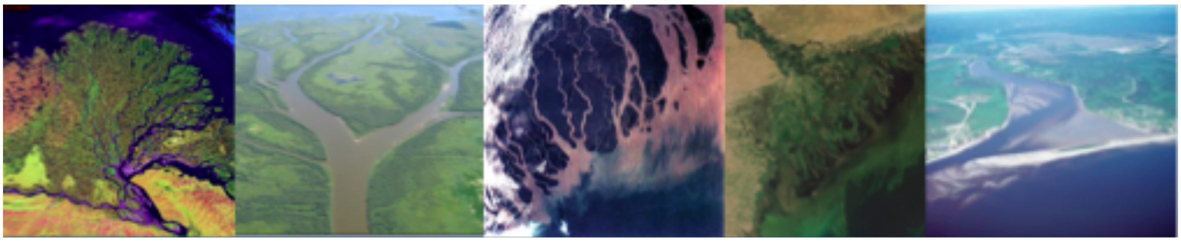

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DELTAS: Catalyzing Action Towards Sustainability of Deltaic Systems with an Integrated Modeling Framework for Risk Assessment

Introduction

Deltas are dynamic landforms at the land-ocean boundary, involving intricate mazes of river channels, estuarine waterways, and vast, often flooded landscapes. They cover 1% of Earth, yet are home to over half a billion people. Deltas sustain biodiverse and rich ecosystems, such as mangroves, reedlands and marshes. They are also economic hotspots that support major fisheries, forest production, and agriculture, as well as major urban centers, ports, and harbors.

Yet, worldwide delta systems, including the people, economies, infrastructure, and ecology they support, are under threat from a range of natural and anthropogenic activities. Dammed rivers upstream deprive deltas of critical water and sediment for continued viability. Local oil and gas exploration contributes to deltaic subsidence, loss of wetlands, and accelerated erosion. These human dimensions and ecological implications of deteriorating or disappearing deltas cannot be overstated. Moreover, these drivers of change are being compounded by the effects of climate change. There is an urgent need to rally the international community for a focused effort toward a holistic physical-socioeconomic understanding of deltas as vulnerable systems undergoing change. Such understanding is a basic requirement for their long-term management, protection, and restoration.

Recognizing this need, the Belmont Forum, an international collaboration of funding agencies, has identified coastal vulnerability as a focused priority, with an overarching goal "to deliver knowledge needed for action to mitigate and adapt to detrimental environmental change and extreme hazardous events." In this context, deltaic systems showcase the need to couple our understanding of the physical, ecological, and socio-economic aspects of coastal systems in ways that sustain human interests while protecting the environment from anthropogenic and climate stressors. Indeed, deltas exemplify the much talked about "global change, local solutions" paradigm.

The DELTAS project, led by the University of Minnesota, was selected by the Belmont Forum to develop a science-based integrative modeling framework that can be used to assess delta vulnerability and guide sustainable management and policy decisions at the regional and local scales**.** As one of the funded "Coastal Vulnerability" projects, the main premise of the proposed work is that although each delta is unique, integrative frameworks that capture the socio-ecological working of these systems can be developed and encapsulated in decision support tools that can be adopted locally in different locations, in collaboration with regional experts and stakeholders, for sustainable delta management.

Research Framework and Objectives

Our research framework comprises five different components, referred to as "Work Packages" (WPs):

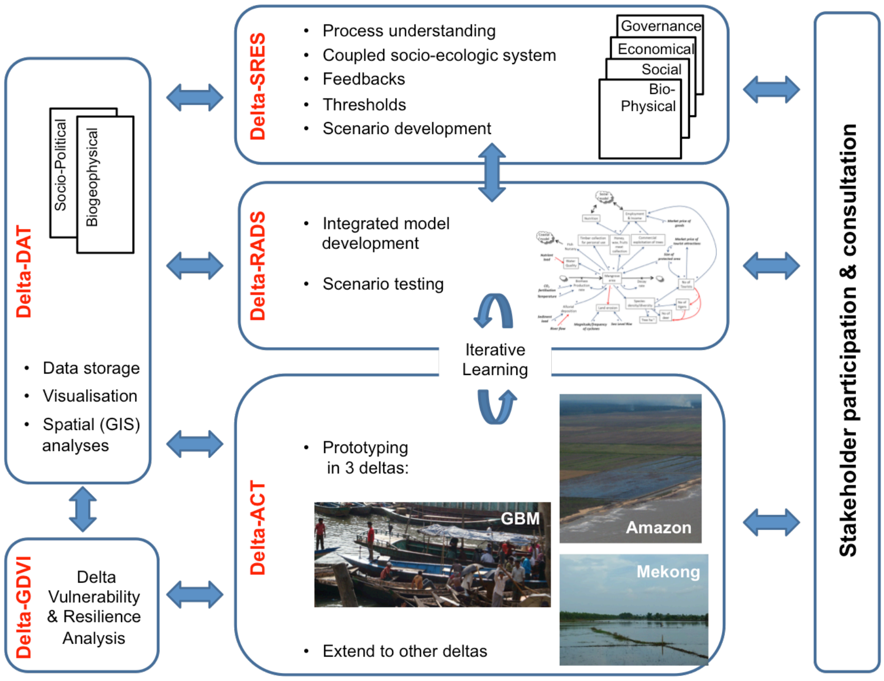
- **Delta-SRES**: *Develop a theoretical framework for assessing delta vulnerability and the possibility for transitions to undesired biophysical or socio-economic states under various scenarios of change.* Delta-SRES will, therefore, advance sustainability science for deltas.

- **Delta-RADS**: Develop *an open-access, science-based, integrative modeling framework called the Delta Risk Assessment and Decision Support (RADS) Tool. This tool will be a GIS modeling system that will support quantitative mapping and definition of functional relationships of the bio-physical environment of deltas as well as their social and economic dynamics. Importantly, it will be* developed via consultation of the users and stakeholders to ensure that it adequately addresses the complex realities of delta management. I*t will be designed so that it can be applied at a* regional level and provides a quantitative basis for investigating and comparing scenarios and trade-offs for decision making. It will provide regional planners with the best science to perform scenario modeling and remediation for their region.

- **<u>Delta-DAT</u>:** *Consolidate data on bio-physical, social, and economic parameters into an international repository of integrated data sets and make these readily available relevant data* for use by the community at large to assess critical parameters, compute vulnerability metrics, and provide input data to the Deltas-RADS modeling framework.

- **<u>Delta-GDVI</u>**: *Develop Global Delta Vulnerability Indices that capture the current and projected physical-social-economic status of deltas around the world ("delta vulnerability profiles").* The GDVI will be presented in a spatially explicit, GIS, format at high spatial resolution. It can be used to identify and support the critical needs and priorities for research, funding, and action

- **<u>Delta-ACT</u>:** Work with regional teams and stakeholders to *put the products of Delta-SRES, Delta-RADS and Delta-DAT into action* by demonstrating the implementation of the developed framework to three major deltas. The selected deltas are the Ganges-Brahmaputra-Meghna (GBM), Mekong, and Amazon deltas. These deltas were selected as they are each globally significant and encompass a range of physical and social environments. In addition, the DELTAS team has extensive experience in these systems and will leverage numerous ongoing research projects and regional contacts to form a foundation for adapting our framework to other deltas around the world.



Key components of the DELTAS project, whereby deltas are treated as fully coupled socio-ecological systems and scientist-stakeholder feedback is emphasized at all levels.

Using the above framework, the DELTAS project will investigate several key questions in delta functioning and vulnerability, towards proposing sustainable solutions. These questions include:

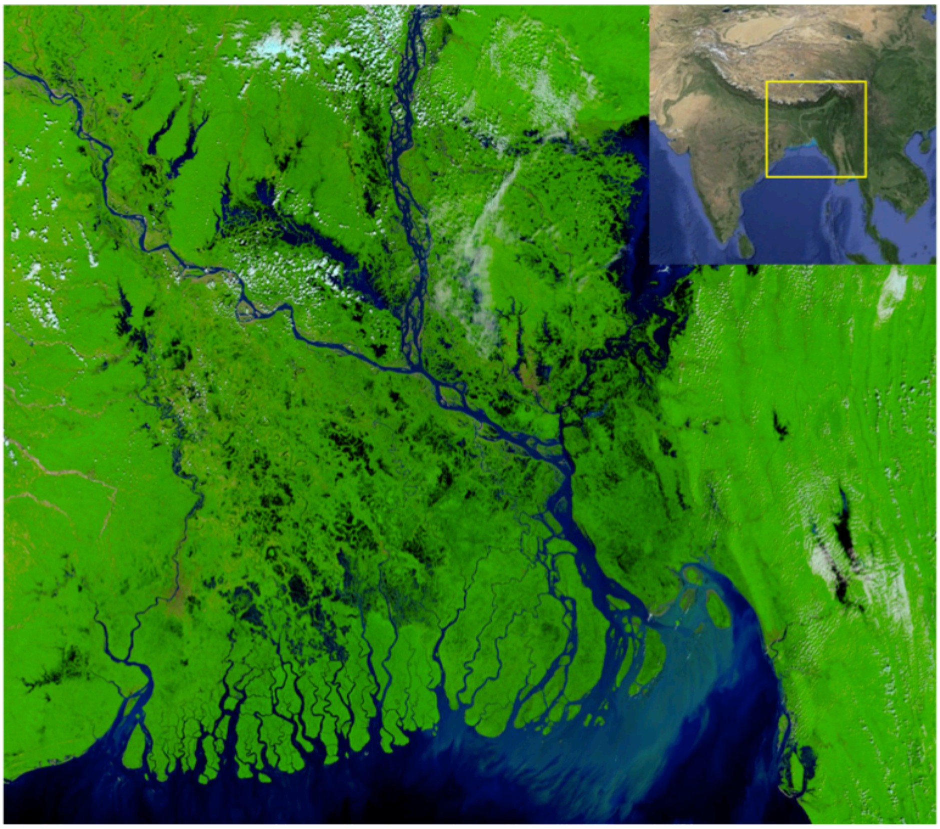
(1) How do climate change, pressure on resources, and engineering/ infrastructure development make delta people, biodiversity, and ecosystems vulnerable?
(2) How is this vulnerability to be measured?
(3) How do delta areas absorb extreme events? What are the hydrological and ecological thresholds underlying the integrity of a delta region?

(4) What are the relevant local and regional biophysical and social 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?

A. The Ganges-Brahmaputra-Meghna (GBM) Delta

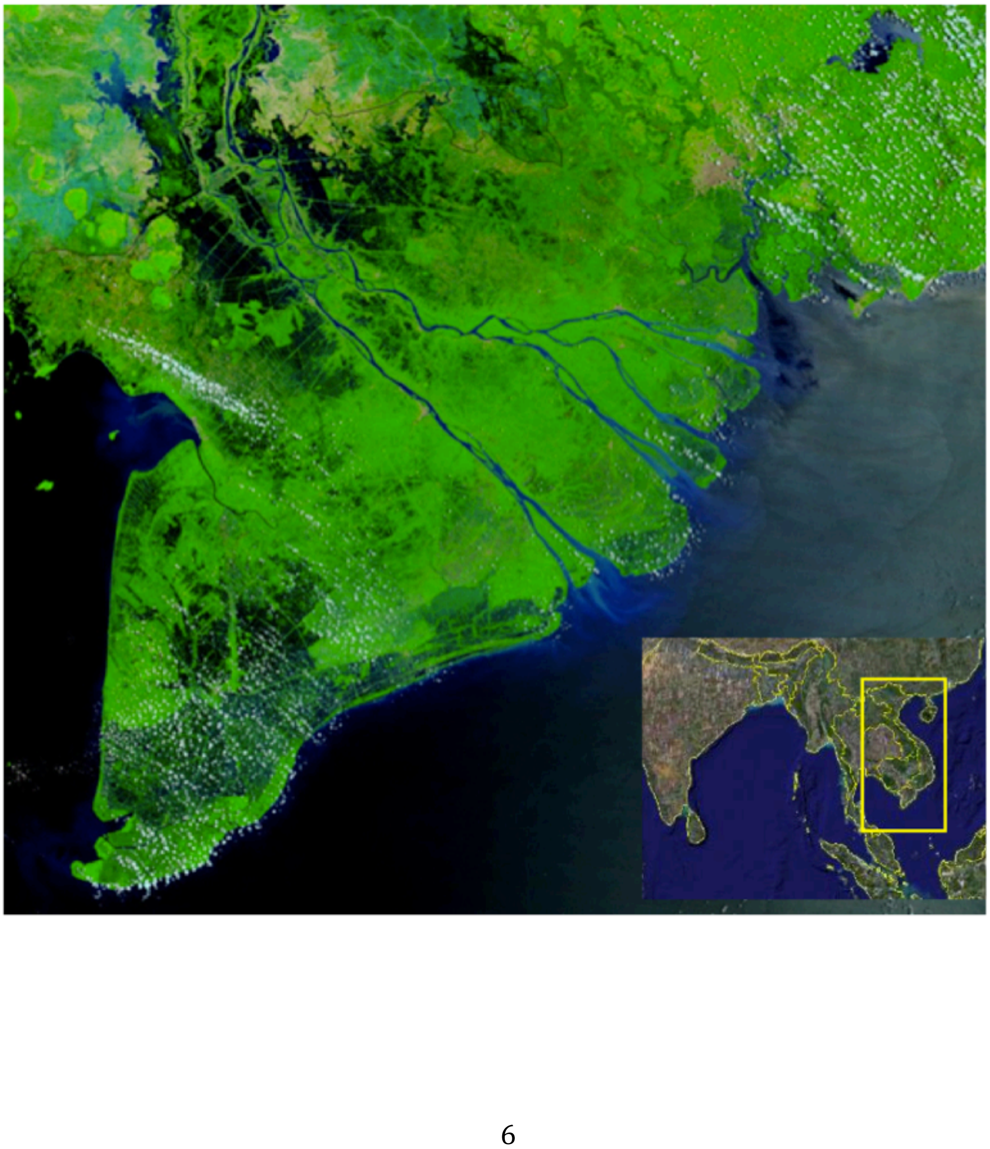
The GBM Delta is one of the world's largest (~100,000 km^2) and most dynamic deltas draining land from Bangladesh, Bhutan, China, India and Nepal. The delta covers most of Bangladesh and part of West Bengal, India, with many of the 147 million people (in 2000) living in the delta under extreme poverty and facing multiple challenges. The population is expected to increase by 28% by 2015 [*Overeem and 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 and Goodbred*, 2005].

Ensemble CCSM experiments predict 11% higher rainfall during the Asian monsoon [*Meehl and Washington*, 1993; *May*, 2004; *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.



B. The Mekong Delta

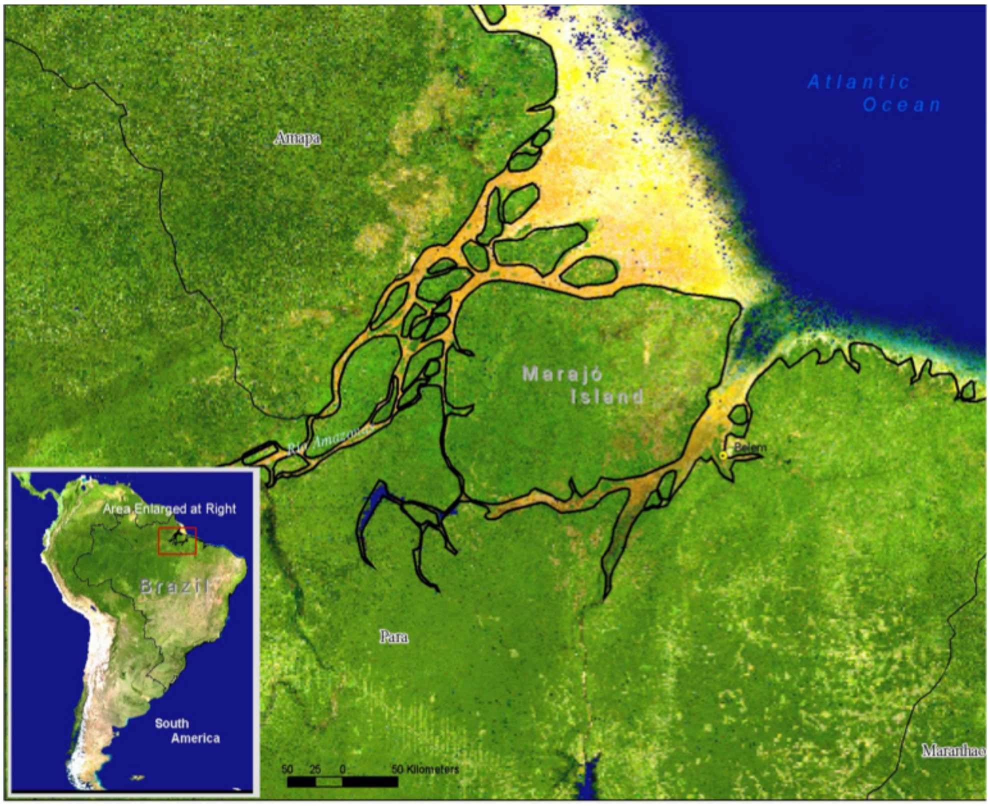
The Mekong Delta is considered as the world's third largest delta (with an area of 93,781 km^2 and population of 17 million), is one of Asia's main food baskets, and is second only to the Amazon in terms of fish biodiversity [*WWF*, 2008]. The major challenges in the MRD can be attributed to socio-economic transformation and urbanisation processes leading to the degradation of the last natural forest and wetland areas, accompanied by increasing water pollution [*Kuenzer and 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 [*Gebhardt et al.*, 2012; *Leinenkugel et al.*, 2011; *Kuenzer and 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 and 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; *Wang et al.*, 2011; *Xue et al.*, 2011; *Räsänen et al.*, 2012].



C. The Amazon Delta

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; *Anthony et al.*, in press]. 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 and 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.



II. Project Team:

The BF-DELTAS project harnesses the collaboration of several, international and diverse teams of specialists with expertise in physical and social sciences, economics, health and demographics. These teams include government and university researchers, and NGO's, with close relationships to policy makers and managers who are responsible for implementing the actions that will ensure delta sustainability. The BF-DELTAS teams include:

USA: E. Foufoula-Georgiou (University of Minnesota – Lead Institution); I. Overeem (University of Colorado at Boulder); S. Goodbred Jr. and C. Wilson (Vanderbilt University); C. Vorosmarty and Z. Tessler (City College of New York); E. Brondizio (Indiana University)

Japan: Y. Saito (National Institute of Advanced Industrial Science and Technology, acting through Geological Survey of Japan)

Germany: C. Kuenzer (University of Wuerzburg); F. Renaud and Z. Sebesvari (United Nations University, Institute for Environment and Human Security, Bonn, Germany)

France: E. Anthony (Centre National de la Recherche Scientifique, CNRS)

United Kingdom: R. Nicholls, Z. Matthews, J. Dearing, A. Lazar, A. Baschieri and S. Szabo (University of Southampton); N. Burgess, M. Sassen and A. van Soesbergen (World Conservation Monitoring Centre)

India: R. Ramesh (National Centre for Sustainable Coastal Management, Ministry of Environment, Forests and Climate Change); T. Ghosh (Jadavpur University)

Netherlands: M. Marchand and T. Bucx (Stichting Deltares)

Bangladesh: K.M. Ahmed (University of Dhaka); Md.M. Rahman (Bangladesh University of Engineering and Technology)

Vietnam: V. L. Nguyen (Vietnam Academy of Science and Technology); M. Goichot (World Wide Fund for Nature-Vietnam Program Office)

Brazil: S. Costa (University of Vale do Paraíba)

Canada: G. Lintern (Natural Resources Canada); P. Van Cappellen and H. Durr (University of Waterloo)

China: S.Gao (Nanjing University)

Norway: A. Newton (Norwegian Institute for Air Research)

BF-DELTAS Project Partner Countries

III. Principal Investigator (PI) Reports

Efi Foufoula–Georgiou's group

University of Minnesota

Anthony Longjas, Alejandro Tejedor, Zeinab Takbiri, Jonathan Czuba, Mohammad Danesh-Yazdi, Amy Hansen, and Jon Schwenk

Research Themes and Accomplishments during 2015-2016

Our research efforts over the past year have concentrated on four main areas: (1) quantifying the signature of sediment composition on the topologic and dynamic complexity of delta channel networks towards advancing a quantitative delta classification framework; (2) unraveling an optimality principle behind the topology and flow dynamics of observed delta channel patterns; (3) developing an algorithm for improved satellite retrieval of precipitation and flood inundation in deltaic regions; and (4) articulating regional goals for sustainability of deltas as hotspots of change within the framework of Sustainable Development Goals (SDGs). Special emphasis was placed in the Mekong, Ganges, and Amazon river deltas, which are the focus deltas of the DELTAS project funded under NSF Belmont Forum-G8 Collaborative Research. However, the developed frameworks are general and transferable to other deltas.

1. Quantifying the signature of sediment composition on the topologic and dynamic complexity of river delta channel networks and inferences toward delta classification

Deltas contain complex self-organizing channel networks that nourish the deltaic surface with sediment and nutrients. Developing a quantitative understanding of how the controlling physical mechanisms of delta formation relate to the channel networks they imprint on the landscape remains an open problem, hindering further progress on quantitative delta classification and relating process to patterns. We have studied the isolated effect of sediment composition on network structure by analyzing Delft3D river-dominated deltas (Figure 1, top panels) within the recently introduced graph-theoretic framework for quantifying complexity of delta channel networks [*Tejedor et al*., 2015a,b]. We demonstrated that deltas with coarser incoming sediment (less cohesive) tend to be more complex topologically (increased number of pathways) but simpler dynamically (reduced flux exchange between subnetworks) and that once a morphodynamic steady state is reached, complexity also achieves a steady state [*Tejedor et al.* 2016]. By positioning simulated deltas on the so-called TopoDynamic complexity space and comparing with field deltas (Figure 1), we showed encouraging results and provided preliminary evidence towards a path for quantitative delta classification by exploring similarities and discrepancies in the underlying processes and the resulting network complexity. Further research is currently under way to systematically analyze a larger data set of delta patterns generated via numerical modeling and introducing more dimensions in the TopoDynamic space to enhance its discriminatory power.

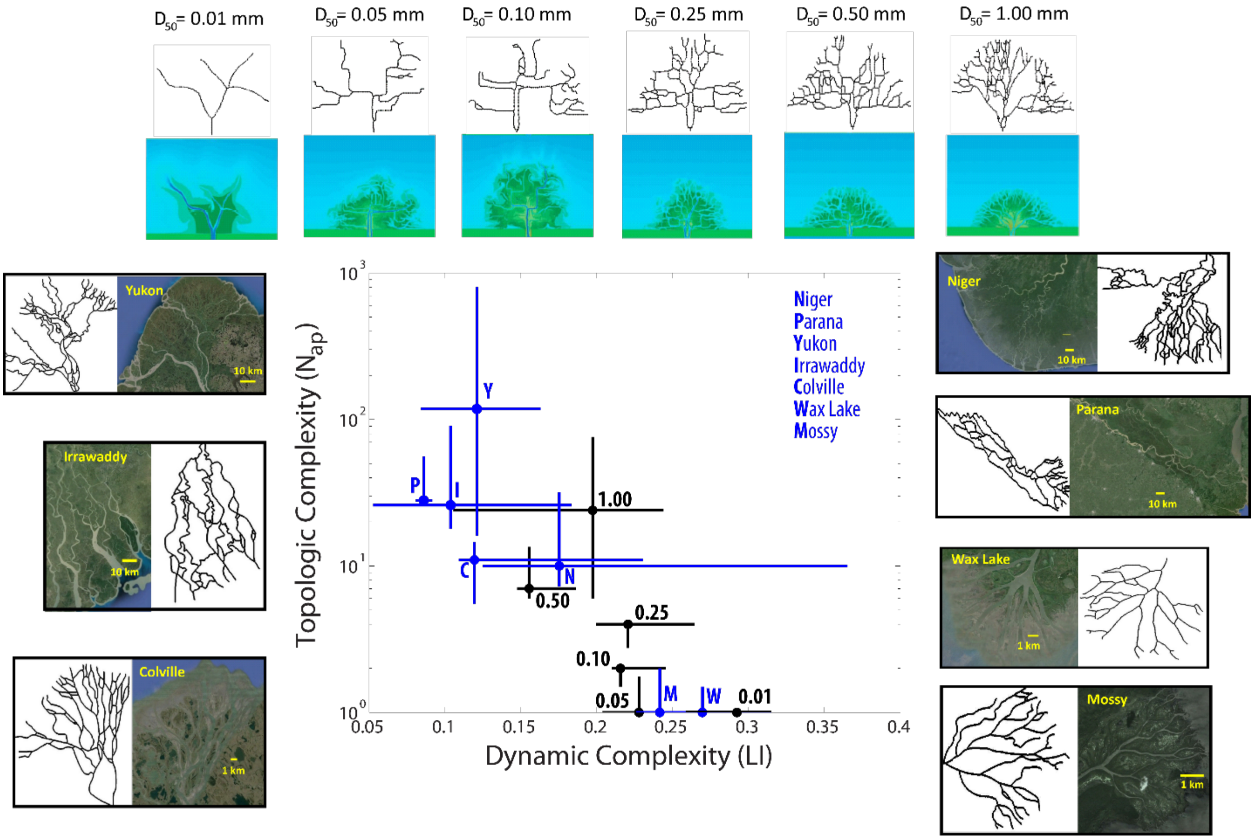


Figure 1. 2D TopoDynamic Space. Combining both the Topological (Number of alternative paths, N_{ap}) and Dynamic (Leakage Index, *LI*) complexity, each delta is positioned uniquely in the TopoDynamic space. Seven field deltas (Niger, Parana, Yukon, Irrawaddy, Colville, Wax Lake and Mossy) and six numerical deltas with different median grain size are displayed. From the numerical deltas we can conclude that fine-grained, cohesive deltas have low topologic complexity and high dynamic complexity. For field deltas, a transition to high topologic complexity and low dynamic complexity is observed as well. The dots correspond to the medians of both parameters, i.e., Number of alternative paths and Leakage Index, while the vertical and horizontal lines span the corresponding 25th up to the 75th percentiles.

Publications:

Tejedor, A., A. Longjas, R. Caldwell, D. A. Edmonds, I. Zaliapin, and E. Foufoula-Georgiou (2016), Quantifying the signature of sediment composition on the topologic and dynamic complexity of river delta channel networks and inferences toward delta classification, *Geophys. Res. Lett.*, *43*, doi:10.1002/2016GL068210.

Brondizio, E., E. Foufoula-Georgiou, S. Szabo, N. Vogt, Z. Sebesvari, F. G. Renaud, A. Newton, E. Anthony, A. V. Mansur, Z. Matthews, S. Hetrick, S. M. Costa, Z. Tessler, A. Tejedor, A. Longjas, J. A. Dearing (2016), Catalyzing action towards the sustainability of deltas, *Current Opinion in Environmental Sustainability*, *19*, 182-194, doi: doi:10.1016/j.cosust.2016.05.001.

2. Is there an optimality principle behind delta channel patterns?

Our previous works [*Tejedor et al.*, 2015a; 2015b; 2016] have shown how some information of the physical processes that shape deltas is engraved in their channel network complexity. The challenge now is trying to understand the self-organization of deltas in terms of first order principles, asking questions such as: are deltas trying to achieve an optimality of some sort in terms of maximizing/minimizing an objective function during their development? Are deltas self-organizing in a way that they maximize (minimize) resilience (vulnerability)? How do anthropogenic influences affect delta self-organization and does this project itself as sub-optimality compared to natural deltas?

We have developed a new metric of Entropy Rate (ER) that captures the information content of a delta network in terms of the degree of uncertainty in delivering fluxes from any point of the network to the shoreline [*Tejedor et al.,* 2016 in preparation]. Our preliminary results for field and simulated deltas (Delft 3D) show that channel widths self-adjust such that the delivery of fluxes from the delta top to the shoreline has a maximal value of Entropy Rate, as shown for example in Figure 2. These results have important implications since entropy and resilience are related by the fluctuation theorem [*Demetrius and Manke*, 2005], and therefore suggest that deltas might in fact self-organize to maximize their resilience to perturbations.

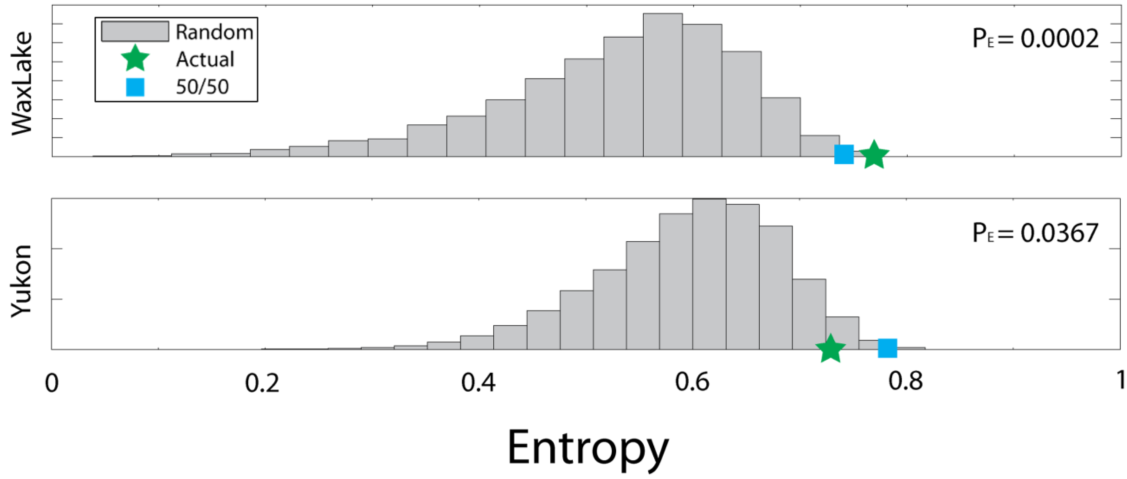


Figure 2. Entropy Rate and delta self-organization. For the case study of two deltas, Wax Lake (Top) and Yukon (Bottom), the Entropy Rate (marked as entropy above) is computed as the normalized average uncertainty of delivering fluxes from the delta top to the shoreline when flux partition is modeled using the current widths (green star) and 50-50 partition at each bifurcation (blue square). A frequency histogram corresponding to the entropies computed for "random deltas" each produced by randomization of the weights at every bifurcation (i.e., random partition of fluxes at each channel bifurcation) according to a uniform distribution is displayed as well. These preliminary results show that the value of entropy corresponding to the actual widths of the delta is maximal, such that the probability of exceeding this value of entropy (P_E) by a random realization is lower than 0.05.

3. A new Algorithm for Satellite Retrieval of Flood Inundation over Deltaic Regions

In situ data of water coverage over deltaic surfaces are usually sparse and preclude the accurate monitoring of regional flood inundation dynamics at high space-time resolutions. Multi-satellite observations offer valuable information in that respect but conversion of what the satellite observes to flood inundation on the ground is not a simple task. We have developed a flood inundation multi-sensor passive retrieval algorithm that takes advantage of the capabilities of both spaceborne microwave radiometers and visible to near infrared spectroradiometer, thereby allowing detection and mapping of inundated areas under almost all-sky conditions. The proposed method, based on a Bayesian retrieval algorithm, relies on the nearest neighbor search and a modern sparsity promoting inversion method recently developed in our group for satellite rainfall retrieval [*Ebtehaj et al*., 2015]. The inversion method makes use of a priori database in the form of two joint dictionaries that contain brightness temperatures from overlapping observations by the Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) and visible and infrared observations from the Moderate Resolution Imaging Spectroradiometer (MODIS). The term "inundation" here means regions where water covers the land surface, not necessarily in a destructive mode, e.g., coastlines, small water ponds, rice fields, flooded areas, etc. We use the daily global observations of visible and near infrared (VIR) data from MODIS on board Terra and Aqua satellites (launched in Year 1999 and 2002, respectively) and passive microwave data from the SSM/I on board Defense Meteorological Satellite Program (DMSP) satellites F8, F10, F11, F12, F13, and F15 (Launched in Year 1987, 1990, 1991, 1994, 1995, 1999, respectively) and the SSMIS on board DMS satellites F16, F17, and F18 (launched in Year 2003, 2006, and 2009, respectively). Several years of concurrent collocated observations (1999-present) by these sensors allow us to collect adequate overlapping data under non-cloudy condition to build the a priori database. The overlapping data then are used to link coarse scale SSM/I and SSMIS passive microwave data to high-resolution MODIS visible/near infrared inundation fraction data in the form of an organized database, which can be used for passive microwave retrieval of inundated areas under almost all sky condition. The database is organized into two fat matrices, the so-called brightness temperature and inundation dictionaries. For an observed pixel-level of brightness temperatures the proposed passive retrieval uses the nearest-neighbor search to isolate a few profiles of brightness temperatures and their corresponding inundated measures in a Euclidean sense. Then, those neighbors are used to estimate the unknown inundation fraction of each vector of passive microwave observation by estimating the representation coefficients that linearly approximate an observed brightness temperature by its nearest neighbors [*Takbiri et al.*, 2016 in preparation].

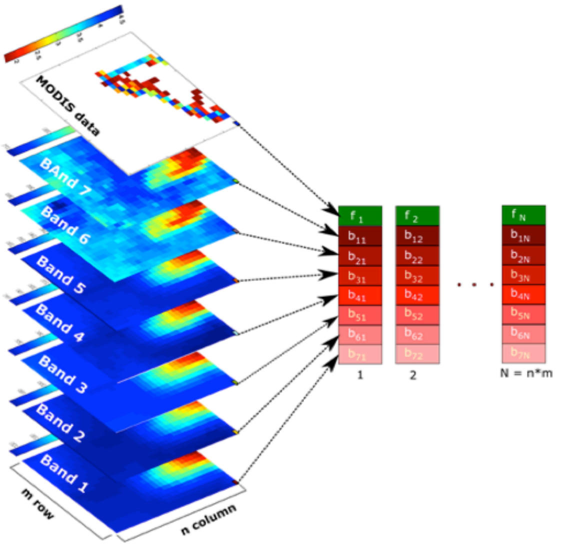


Figure 3. Creating the a priori dictionary. The top slab is the upscaled MODIS data and the other seven slabs are the brightness temperature (T_b) data at seven frequency bands. Each vector on the right is created by the corresponding pixels at the 8 matrices of observations i.e., seven Tbs and one inundation fraction at 12.5 km by 12.5 km pixel. N vectors (N = n x m) consist of seven Tbs and one corresponding inundation fraction, which are obtained at each day (temporal resolution of the data is one day). Only one image obtained in one day is shown in this picture. For every day in 5 years, there are n x m vectors of length 8.

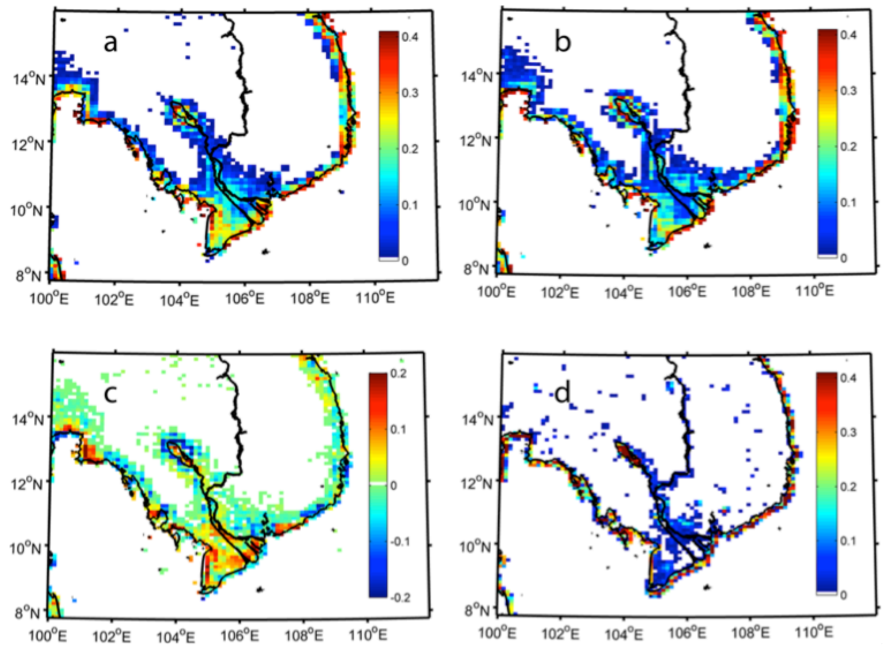


Figure 4. Results of the proposed algorithm. The average inundation fraction for July-December in Year 2015 for (a) Ascending and (b) Descending orbital dictionary in the Lower Mekong region. For each day in these five months the inundation fraction is retrieved for every 12.5 km by 12.5 km pixel using the proposed algorithm and then the six-month average of inundation maps illustrated in a and b are obtained. The difference between the average inundation fraction of “Ascending” vs “Descending” orbit (c) reveals the larger inundation fraction for

"Ascending' orbit compared to the "Descending" orbit. The MODIS data at 250 m by 250 m for the same time period upscaled to 12.5 km by 12.5 km (d) show good agreement with the results obtained using the developed retrieval algorithm.

4. Delta sustainability within the Sustainable Development Goals (SDGs) Framework

4.1. Imperatives for sustainable delta futures

River deltas are significant in the global economy and support large human populations and biodiversity. Hence, they are now recognized as central to research and policy in the context of environmental change and regional sustainability [*Vörösmarty et al.,* 2009; *Kuenzer and Renaud*, 2012; *Szabo et al*., 2015a]. Human interventions and climate change are increasing environmental risk in many deltas of the world [*Blum and Roberts*, 2009; *Overeem et al*., 2009; *Syvitski et al*., 2009; *Renaud et al.,* 2013]. Land use transition, changing livelihoods and the proliferation of engineering approaches for water management and coastal protection produce unintended outcomes [*Giosan et al.,* 2014; *Auerbach et al.,* 2015]. It is essential to integrate our understanding of the physical, ecological and socio-economic dynamics of deltas to develop systemic understanding and sustainable delta futures [*Foufoula-Georgiou et al*., 2013; *Ramesh et al.,* 2016].

A global initiative, "Sustainable Deltas 2015" supported by the Belmont Forum funded DELTAS project and endorsed by the International Council of Scientific Unions (ICSU), spearheads global efforts towards improving the integrated understanding of deltas. Deltas, due to their global relevance, require targeted attention and action to achieve the Sustainable Development Goals (SDGs). As part of the "World Oceans Day", NSF featured our BF Deltas project in a news article:
http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=138738&org=NSF&from=news.

4.2. Making SDGs work for climate change hotspots

Deltas are dynamic systems that are characterized by low elevation, frequent flooding and high biodiversity; and they benefit from high agricultural and fisheries productivity, contributing to regional and global food security. Climate change is leading to higher sea levels, to changes in major river discharge and likely to increases in the frequency of cyclones and coastal storms in many susceptible areas. Collectively, this increases the risk of floods and salinization, often intensified by natural and human-induced land subsidence, and will affect coastal ecosystems and the services they provide. Two other "climate change hotspots" are: *Semi-arid regions* (home to more than 2 billion people, most of them living in developing countries) which are drylands already experiencing harsh climatic conditions and particularly vulnerable to degradation and desertification, and *Glaciers and snowpack-dependent river basins* (home to more than one sixth of the world's population, or over 1.2 billion people) which face severe challenges in a warmer climate, including declines in both seasonal snowpacks and glaciers, changes in glacier and snowpack melting, and thus water release, putting additional pressure on dams and groundwater resources. Together, the threats to these climate hotspots (Figure 5) are exacerbated by projected high levels of population growth, directly affecting the lives of local people, and triggering the potential for increased population movement. Given the importance of climate hotspots to societal and ecological well-being, failing to adequately monitor the environment of these regions may impede their developmental progress, and also hamper the achievement of wider SDGs.

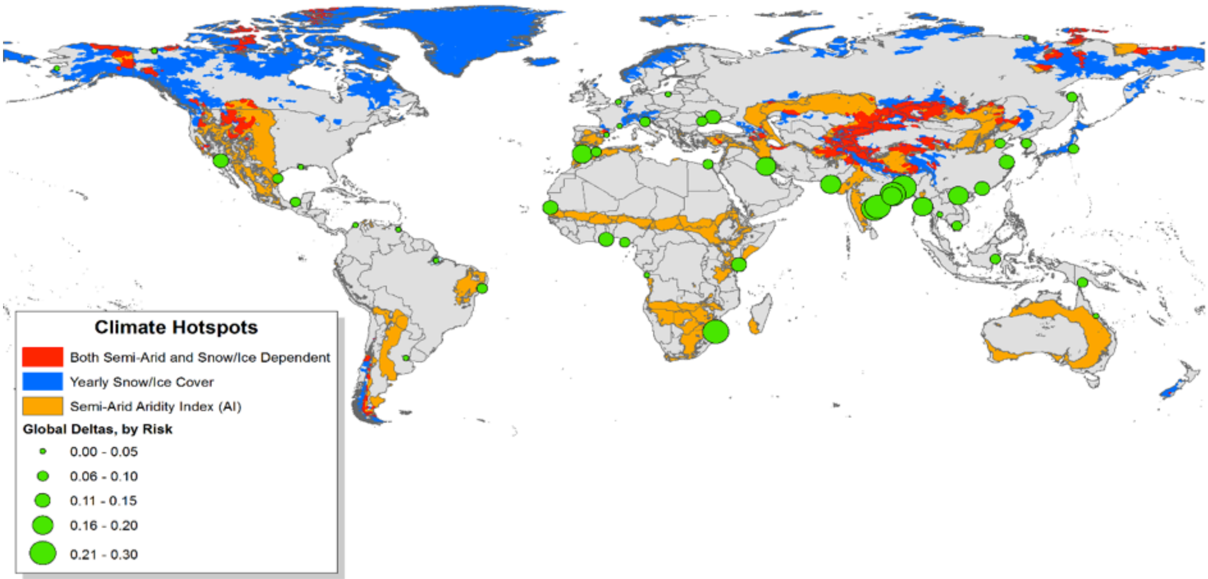


Figure 5. Climate change hotspots requiring focused attention using the Sustainable Development Goals (SDG) indicator framework. The three major types of climate hotspots used in the SDG framework are shown, including: (1) major global delta locations (green dots), varied according to contemporary risk due to sea-level rise and anthropomorphic factors as outlined by Tessler et al. [2015]; (2) semi-arid regions (orange) where an Aridity Index (AI) falls between 0.2 and 0.5; (3) snow and ice runoff-dependent basins (blue), defined as basins with average yearly snow/ice cover $\geq$25%; and (4) overlapping areas with both semi-arid AI and snow/ice runoff dependency (red).

A potentially powerful solution is to translate the existing SDG framework into an *integrated multi-scale indicator framework*, which would: 1) reflect the key developmental challenges found in all of these climate hotspots, and 2) allow monitoring of change at different levels of analysis, including for cross-boundary regions. At the global level, the main indicators would reflect the key international priorities in terms of combating worldwide consequences of climate change; and at the sub-national level the framework would be tailored to the requirements of the country. Here, in addition to measuring such climatic and environmental phenomena as temperature rise, precipitation change and sea-level rise, the developmental priorities should encompass the needs of the Least Developed Countries (LDCs) and allow for tracking of resources for development. Cross-boundary regional indicators should mirror the developmental priorities in the climate hotspots, which have critical implications beyond the areas where they are located. These ideas for making SDGs more relevant to deltas will be further explored over the coming year [see section 4.3 below and also *Tessler et al.*, 2015; *Sebesvari et al.*, 2016; *Szabo et al.*, 2015; *Szabo et al.*, 2016].

4.3. Sustainable Development Goals Offer New Opportunities for Tropical Delta Regions

Deltas are key contributors to agricultural production at the national and regional levels and thus enable alleviation of global food insecurity risks. In addition, tropical megadeltas sustain rich ecosystems that provide a variety of services and are noted for high biodiversity and natural resources. At the same time, however, their geographical location, coupled with often poor land use and river basin management, implies that deltas, more than other coastal areas, are prone to natural hazards and disasters such as subsidence, flooding, coastal erosion, and cyclones/typhoons. These environmental shocks have been proven to lead to high out migration and threaten human security in already relatively economically poor regions. Climate change, in particular sea-level rise, exacerbates the existing vulnerabilities by increasing the risks of rapid-onset disasters, as well as creeping processes such as salinity intrusion.

We discuss new opportunities for the way that the proposed Sustainable Development Goals (SDGs) agenda interacts with delta regions and highlight key policy measures needed to address the existing gaps. The proposed SDGs present clearly a number of concrete opportunities for tropical delta regions. First, they constitute a move in the right direction by recognizing climate change among the key priorities, along with an explicit recognition of inequality as one of the major obstacles to sustainable development. The proposed SDGs also mention the right to environmental protection and the need to integrate socioeconomic and environmental aspects of development at national and regional scales. Moreover, the importance of subnational differences and the need for location specific disaggregated data are explicitly acknowledged, which opens the door for a contextualized approach.

These are all welcomed advancements in terms of relevance to the challenges faced by populations of tropical deltas.

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Future Research (2016–2017)

In the next year our focus will be along the following lines:

1. Delta channel network topology and dynamics for delta comparison, physical inference and vulnerability assessment.

1. We will analyze delta channel network evolution using historical data and also simulated deltas using Delft 3D to quantify how delta complexity evolves over time and in particular how it responds to abrupt changes in system topology and dynamics, due for example to avulsions.
2. We will quantify how channel network complexity might change as a function of the scale at which the channels are resolved. What can be learned from such a multi-scale analysis of complexity?
3. We will explore additional metrics to the ones we have introduced so far (number of alternative paths and Leakage index) to extend the dimensionality of the TopoDynamic space in a way that enhances classification. Parameters will include: Island shape, size and orientation (important for tidal deltas), shoreline properties, upstream streamflow and its variability, sediment cohesiveness, land-use and ecosystem properties, etc.
4. We have begun asking the question: *what optimality do delta channel networks try to achieve?* We have introduced a notion of Entropy Rate (ER) specific to deltas and have shown that simulated deltas and several real deltas have ER which is close to the maximum rate among patterns of the same topology but different dynamics as projected into different flow distributions in channel junctions. This work will continue by analysis of the dynamic evolution of simulated deltas of known physics.

5. We will relate entropy to previously established and novel indices of vulnerability to quantify the relationship among these quantities.
6. We will analyze the impacts of direct (e.g., construction of divergence structures to satisfy demands for water and energy (dams, ditches), intensive agricultural use, etc.) and indirect (e.g., Relative Sea Level Rise) anthropogenic alterations on the self-organization of deltas, and therefore in their capacity to withstand perturbations.

2. Improved Satellite Rainfall Retrieval and Flood Inundation over Deltas and Coastal Zones

1. We will test the developed passive microwave rainfall retrieval algorithm (ShARP) over coastal areas and deltas using the collected TRMM overpasses over Ganges, Mekong, and Amazon for a five-year period.
2. We will test and further refine the developed algorithm for flood inundation over delta regions at high spatial and temporal resolutions and examine how this can be used in real-time and predictively for vulnerability assessment and warnings.
3. We will collaborate with other members of the BF-DELTAS project to assess how the developed remotely sensed tools can be verified using available ground-based observations.

Group Publications 2015-2016 (partially funded by this grant)

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Foufoula-Georgiou, E., A. M. Ebtehaj, and R. Bras (2015), "A Novel Bayesian algorithm for Microwave Retrieval of Precipitation from Space: Applications in Snow and Coastal Hydrology", EGU2015-7585, EGU General Assembly, Vienna, Austria, 12-17 April. [SOLICITED]

Foufoula-Georgiou, E., J. Schwenk, and A. Tejedor (2015), "Perspective – Open problems in earth surface dynamics require innovative new methodologies from graph theory and non-linear analysis", EGU2015-8805, EGU General Assembly, Vienna, Austria, 12-17 April.

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Hansen, A., J.C. Finlay, J.A. Czuba, C. Dolph, and E. Foufoula-Georgiou (2015), "Assessing Wetland Effects on Nitrogen Reduction within a Fluvial Network Perspective: A Combined Field and Modeling Approach", B53H-02, AGU Fall Meeting, San Francisco, California, 14-18 December.

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Longjas, A., A. Tejedor, and E. Foufoula-Georgiou (2016), "An entropy-based quantification of channel network complexity", CSDMS-SEN Annual Meeting, Boulder, Colorado, 17-19 May.

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sediment-mechanistic properties with metrics of delta channel network topology and dynamics", GC44C-03, AGU Fall Meeting, San Francisco, California, 14-18 December.

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Tejedor, A., A. Longjas, I. Zaliapin, and E. Foufoula-Georgiou (2016), "A graph-theoretic approach to infer process from form in deltaic systems", 31st IUGG Conference on Mathematical Geophysics, Paris, 6-10 June.

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Irina Overeem and Stephanie Higgins
Community Surface Dynamics Modeling System

Research Themes and Accomplishments during 2015-2016

1. Delta-RADS Tool Development

The objective of Integrated Work Package 2 is to develop an open-access, science-based, integrative modeling framework called the Delta Risk Assessment and Decision Support (RADS) Tool. In Year 2, we reported the development of watershed delineation utilities that are a foundation of Delta-RADS. With these utilities, the user specifies the latitude and longitude a point of interest along a river, and new Python wrappers automatically execute routines from the open-source Terrain Analysis Using Digital Elevation Models (TauDEM) program (David Tarboton, Utah State University). The drainage basin river network is delineated and watershed boundaries are established. Resulting shapefiles and raster datasets can be downloaded and opened with any GIS program, including ArcMAP or the open-source GRASS or QGIS. The fully open-source Geospatial Data Abstraction Library (GDAL) had also been wrapped in order to allow users to cut any raster dataset. These tools were substantial and necessary steps towards the full development of Delta-RADS, as they delineate the catchments that contribute water, runoff and sediment to any user-specified delta system.

In Year 3, these tools have been incorporated and expanded to complete the full Delta-RADS processing chain. The Delta-RADS processor is now an open-source, comprehensive GIS tool-chain that produces both spatially variable raster datasets and basin-averaged quantities of the following model inputs:

1. Anthropogenic influence in the river basin, derived from global rasters of population density (CIESIN 2016) and Gross National Product per capita (after Syvitski & Milliman, 2007)
2. Monthly mean and daily standard deviation of precipitation, derived from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) monthly global gridded dataset, 1979 to present (Xie & Arkin, 1997)
3. Monthly and long-term mean monthly values and standard deviations for surface air temperature, derived from the National Centers for Environmental Modeling (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis 1 dataset, spanning 1948 to the present (Kalnay et al., 1996) (Fig 1).*

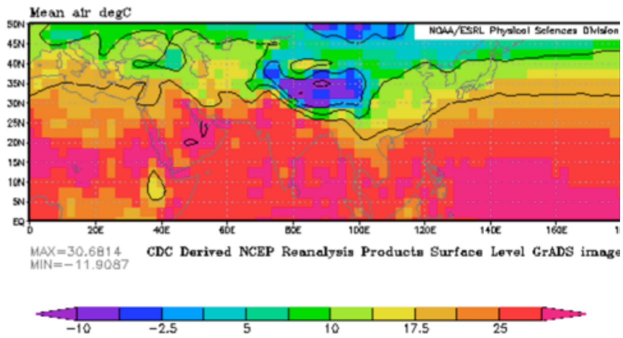

Figure 1. Example 2.5 degree x 2.5 degree gridded raster of mean air temperature for the eastern hemisphere from 0 – 50 degrees latitude, from NCEP/NCAR Renalysis 1 dataset. Using the DELTA-Rads tool, the user can enter any latitude and longitude of interest, and the Reanalysis Dataset will be processed to derive monthly mean and inter-monthly standard deviations of air temperature over any user-specified time range restricted to the user-specified catchement.

**Both the NCEP reanalysis data and the CMAP precipitation data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at* http://www.esrl.noaa.gov/psd/

4. Lapse rate and glacier Equilibrium Line Altitude (ELA), which are latitudinally-controlled parameters calculated using empirically-derived relations from Syvitski & Milliman (2007)
5. Basin properties, including topography, relief, area, river length, and hypsometric curve, derived from the USGS 'Hydro1k" hydrologically-corrected digital elevation model of the world
6. Lithology of the basin, along with an erodibility-factor derived from Syvitski & Milliman (2007)
7. A list of the World Meterological Organization (WMO) weather stations in the watershed, with a link to download the corresponding datasets (Fig 2)

These Delta-RADS global datasets (320 GB) have been reformatted, pre-processed, and stored on the supercomputer *Beach* to allow Delta-RADS to process any user-specified latitude and longitude in the world in under one minute. *The toolchain has been tested on five continents* (North America, South America, Europe, Asia, and Africa) and *can now be accessed on GitHub.*

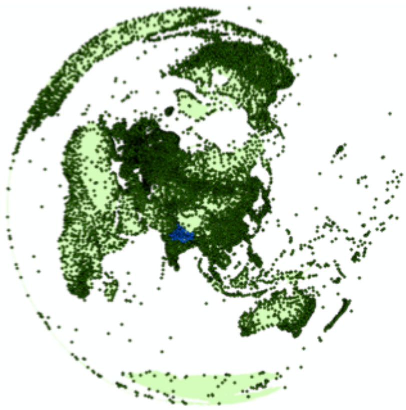

Figure 2. All 10000+ WMO weather stations, with stations of the Ganges Basin shown in blue.

In the remaining months of the project, Delta-RADS will be incorporated into the CSDMS open-source modeling framework "WMT", developed under separate NSF funding. WMT, the Web-based Modeling Tool, provides a graphical interface and a server-side database that allows users to build and run coupled surface dynamics models on a high-performance computing cluster (Syvitski et al., 2014) (Fig. 3). WMT will allow Delta-RADS to be run using a simple web-interface, making the tool chain accessible to users without significant command-line experience.

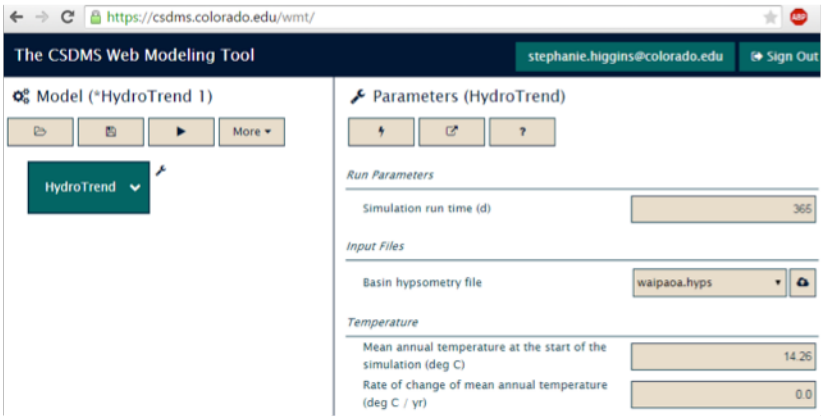

Figure 3. The Web Modeling Tool at csdms.colorado.edu, which allows users to submit modeling tasks to the supercomputer Beach and download output through the web.

2. Delta-RADS Test Study: Indian Rivers Interlinking and its impacts on major deltas

The objective of Integrated Work Package 5, Regional Implementation Case Studies, is to apply the framework of the other work packages to three diverse, globally significant delta systems. In Year 2, we reported using the core service components of the Delta-RADS tool (watershed delineation tools, above) to begin an investigation of the impacts of the Indian Rivers Interlinking project (IRI) on sediment transport to the Ganges-Brahmaputra Meghna delta (GBM). The IRI is an Indian government proposal to link several of India's major rivers together via a vast network of reservoirs and canals. The project would be the largest water diversion in human history, and construction is underway – the first canal opened in September 2015, linking the Godavari and Krishna rivers. If the Interlink project is completed, fourteen canals will divert water from tributaries of the Ganges and Brahmaputra rivers to drier areas in the south and west of India. This is expected to drastically affect sediment transport to the Ganges-Brahmaputra Delta.

Substantial progress has been made towards quantifying the impacts of the Indian Rivers Interlinking project on sediment transport to the GBM. The study's scope has also been expanded to include four additional threatened river deltas in India: the Krishna, Mahanadi, Godavari, and Kaveri deltas. Achievements of the study in Yr 3 are as follows:

1. A digital database has been constructed, which we believe to be the first database of operating specifications for the project. The database includes dam locations, full reservoir levels, submergence areas, storage volumes, displaced population estimates (Fig 4), and operations estimates; canal locations with operations specifications (Fig 5); and up-to-date river discharge data for the major rivers of the system, including daily sediment discharge data from the Krishna, Godavari, Brahmaputra, and Ganges rivers, current through the year 2015. The objectives of this database are (1) to provide best-estimates of water reductions for the modeling study of sediment transport impacts, (2) to exist as an electronic reference for researchers wishing to examine other impacts of the IRI, and (3) to be in a format that can be easily-updated as the IRI project progresses and plans are inevitably altered. Further database details:
    a) **The database was constructed from the following sources:** National Water Development Agency (NWDA) Feasibility Reports/Detailed Project Reports; digitized and georeferenced NWDA maps; Open Street Map extracts, India-WRIS (Water Resources Information System of India) dam databases; World Bank reports, news articles, scientific journal articles, multiple textbooks, DigitalGlobe/Google Earth satellite imagery, SANDRP (South Asia Network on Dams, Rivers and People) publications, conference abstracts, local government meeting minutes, river data from the Chief Engineer of the Krishna and Godavari Basin Organization, river data from the Government of Bangladesh, Integrated Hydrological Data Books from the Central Water Commission of India, Geotechnical investigations by the Geological Survey of India Geotechnical investigations; and publications from the Ministry of Energy, Government of Nepal.
    b) **The database is available in the following formats:** .txt, .csv, .shp (shapefile/geodatabase), and Neo4J (a NoSQL directed graph database). Also available are sets of watershed changes (GeoTIFF files) that would result after IRI implementation, which will be hosted online to facilitate additional studies of the ecological and social impacts of IRI.

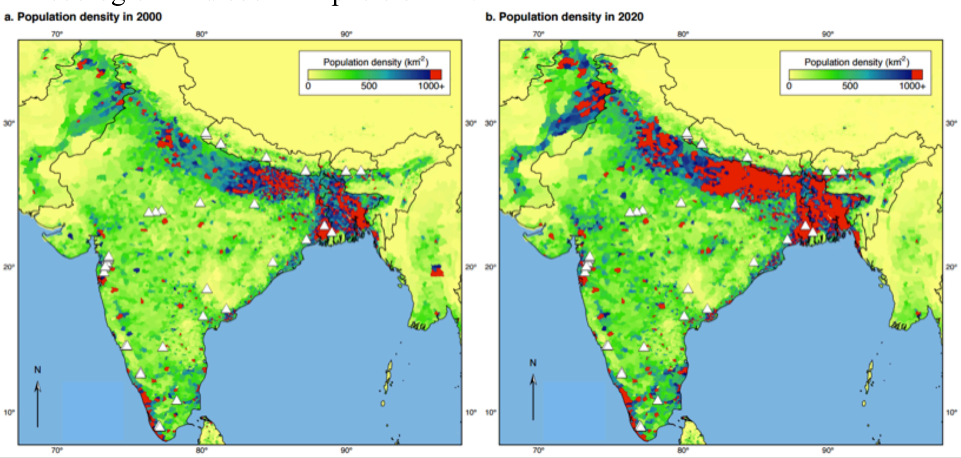

Figure 4. Locations of all 44 proposed dams (white triangles) of the IRI project, overlain on (a)

population density in the year 2000, and (b) estimated population density for the year 2020. In Higgins et al. (2016, *in* prep), the dams database includes displaced population estimates. To calculate expected displaced population, Indian government census estimates (where they existed) were extrapolated from their collection date (typically 1989-1993) to the year 2020 using the population growth rate at the locations of the dams. Where no census existed, displaced population was estimated using population density and submergence area. Population data from CIESIN (2016).

2. Numerical modeling of dam and canal impacts is near completion**,** providing a quantitative estimate of the impacts of the IRI project on sediment transport to the five deltas. The study uses the model HydroTrend v. 3.0, a climate-driven hydrological water balance and transport model that produces daily synthetic time series of water and sediment fluxes (Kettner & Syvitski, 2008). Validation data for the control (no-IRI) model run has been obtained from the governments of India and Bangladesh, who provided daily water and sediment discharge data from four of the five delta apexes spanning the years 1968-2015. The manuscript is near completion and is expected to be submitted for publication shortly.

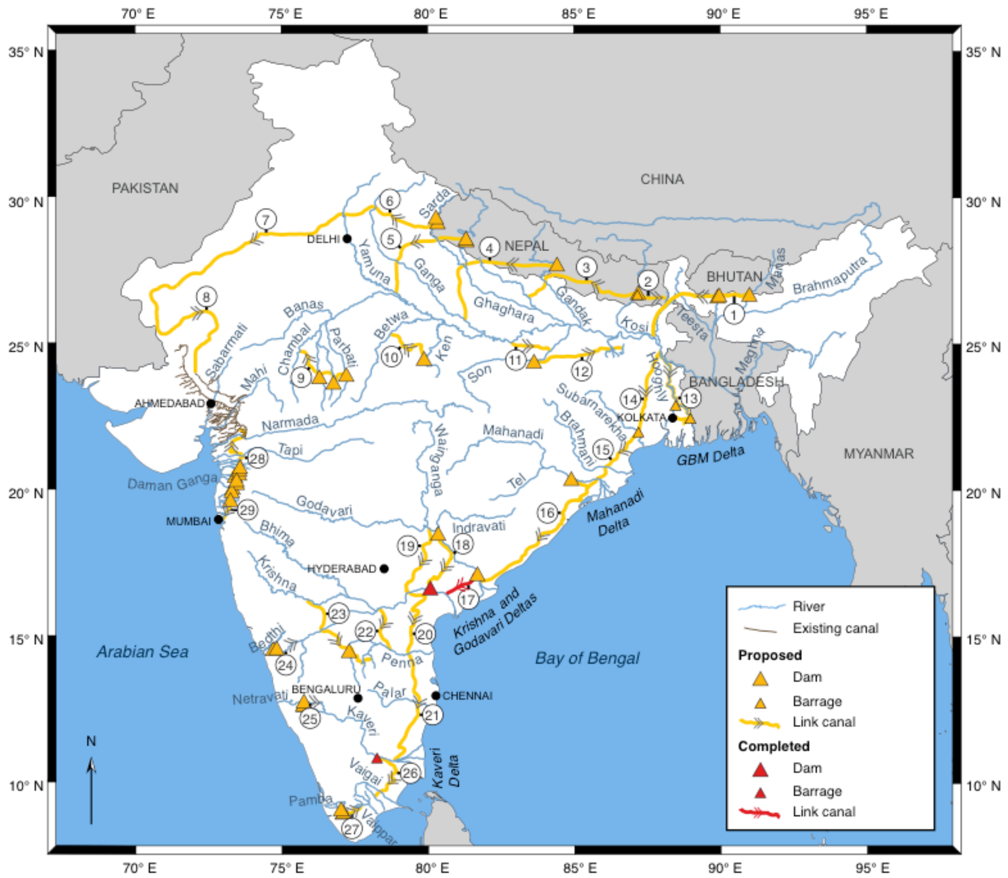

Figure 5. Proposed canals, dams and barrages associated with the Indian Rivers Interlink Project, from *Higgins et al.* (2016, *in prep*). The locations and operating details of each structure are available in .csv and geodatabase formats. Major river deltas are shown - the Ganges-Brahmaputra Meghna (GBM), Mahanadi, Krishna, Godavari and Kaveri - which may lose shoreline due to reduced water flows and increased sediment impoundment behind the dams. In *Higgins et al.* (2016), the model HydroTrend is being used in conjunction with the updated rivers database to simulate the impacts of impoundments and water transfers on sediment transport through each of the five delta apexes.

Additional Efforts:

PI Overeem is a dataset contributor to Science on a Sphere (SOS) animations, documentation and lesson material on river dams and reservoirs, global wave and energy modeling. Specific examples include the influence of dams and reservoirs on the Mississippi delta and Yangtze delta, wave climates during hurricane Katrina and Superstorm Sandy. SOS animated globes are featured in >100 museums, over 33 million visitors see SOS every year.

Overeem was convener of Session on 'Floodplain Dynamics Through Space and Time', *Annual Meeting of the American Geophysical Union (AGU),* 15-19 Dec 2015, San Francisco, CA, USA.

Postdoctoral research associate Higgins mentored a full-time undergraduate student for the summer through the UNAVCO RESESS (Research Experience in Solid Earth Science for Students) program. RESESS is a summer internship program dedicated to increasing the diversity of students entering the geosciences.

Both PI Overeem and PRA Higgins participated in a semester-long educational-development project through the CU Science Discovery Center, culminating in two half-day exhibits at the Boulder Public Library. The exhibits were constructed by Overeem and Higgins, and they used hands-on activities to teach K-5 students about sediment transport and sinking deltas. http://www.colorado.edu/news/features/public-invited-meet-cu-scientist

Overeem is a guest editor for Elementa on Deltas in the ANthropocene. Expressions of Intent were solicited June 2015, submissions of manuscripts are due October 2016.

Saito, Overeem and Renaud convened a special session at the Japan GU, May 2016, Chiba Japan o. Hosted >16 talks, and 18 posters.

New projects built upon the DELTAS project
RESEARCH: Overeem and other DELTAS team members (i.e. Goodbred, Wilson amongst others) were awarded two SF research projects:

- PI: "Coastal SEES Collaborative Research: Multi-scale modeling and observations of landscape dynamics, mass balance, and network connectivity for a sustainable Ganges-Brahmaputra delta" $398k to CU, 2016-2020.
- PI: "Predicting the future of highly regulated deltas: a case-study of the Colorado River" $50k, NCED-NSF PDF Fellowship program, 2016-2017.

APPLIED: Overeem is a US PI in a Joint Venture proposal between Deltares, DHI consulting companies to the angladesh Water Development Board, with funding from the Worldbank, this project has been selected and is under budget negotiations:

- Bangladesh Morphology and Climate Adaptation, Coastal Embankment Improvement Project,
  Phase-I (CEIP-I), Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)

Looking forward
In the final months of the project, CU-Boulder will:

1. Complete the study of sediment transport to the Indian deltas and submit the manuscript and datasets for publication, including datasets. A preliminary manuscript citation is: Higgins, S. A., Overeem, I., Rogers, K., Syvitski, J. P. M., Brakenridge, G. R., and Kettner, A. J. (2016), Impacts of Indian River Interlinking on Sediment Transport to River Deltas, *Elementa: Science of the Anthropocene*, 2016 (*in prep).*
2. Demonstrate and release Delta-RADS through WMT at a DELTAS WS CUNY, NY, September 2016.

3. Overeem is a guest editor for Special Feature in Elementa on Deltas in the Anthropocene. Expressions of Intent were solicited June 2016, submissions of manuscripts are due October 2016.

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Charles Vörösmarty, Zachary Tessler and Sean Thatcher

CUNY Environmental CrossRoads Initiative

City College of New York/CUNY ASRC

Research Themes and Accomplishments during 2015-2016

Our research over the past year has focused on three main areas:

1. Deltas-GDVI: Environmental Stress and Vulnerability analysis of the Mekong, Amazon, and Ganges deltas relative to a global sample of 48 deltas.
2. Deltas-GDVI: Environmental Stress Typology assessment of the Mekong, Amazon, and Ganges deltas
3. Deltas-GDVI: Coastline change and sediment transport modeling of the Mekong delta

1. Environmental Stress and Vulnerability analysis

We have further developed the Environmental Stress and Vulnerability analysis to include the hazardous event occurrence and social vulnerability indicators. These additional components are essential for quantifying risk to coastal delta populations, as two deltas exposed to similar storm conditions may nonetheless experience substantially different outcomes in terms of harm to local communities.

Relative Sea Level Rise is affected by environmental changes in the upstream, coastal, and offshore domains, and results in changes to coastal flood risk. Our index of delta environmental change, termed the Anthropogenic Conditioning Index, is correlated with estimates of relative sea level rise available in the literature for select deltas. We can use this index as an estimate for relative sea level rise in deltas where direct observations are unavailable. The effect of relative sea level rise in terms of risk is estimated from an *expected loss* model, where loss is the product of the number of people *exposed* to hazardous conditions such as flooding, and the average loss to each person exposed. This loss estimate is a function of the type and intensity of a particular hazard, such as a monsoon-driven river flood, or the storm surge resulting from a tropical cyclone. We then define a probability distribution over all potential hazardous events for a particular delta. Calculating this distribution is difficult, particularly in deltas such as the Mekong, Ganges, and Amazon, with a relatively short data set of historical flood events and outcomes. Instead, we have developed indicators, in parallel with the environmental stress index, to broadly quantify the relative frequency and intensity of hazards on each delta.

The Hazardous Events Index is comprised of tropical cyclone frequency and intensity, M2 tidal amplitude, and standardized 30-yr return levels of river discharge and wave energy. The index is constructed in a similar manner as the environmental stress index, with equal indicator weighting and normalization across all deltas. The Mekong, Ganges, and Amazon deltas are found to have low, moderate, and moderate levels of hazardous event exposure, respectively (Figure 1).

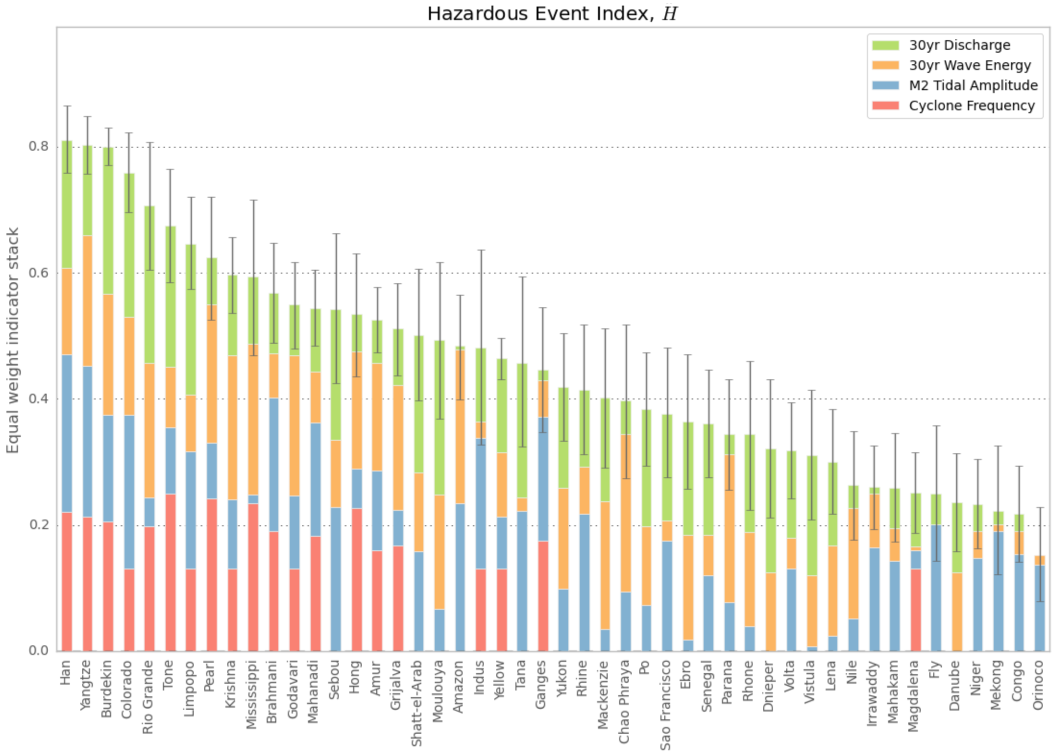


Figure 1. Hazardous Event Index

Additionally, it is important to recognize that a given hazardous event is experienced by a community differently based on the socio-economic context of the delta. The *vulnerability*, or average loss stemming from flood exposure, is estimated as a function of per capital GDP, delta aggregate GDP, and a Government Effectiveness index developed by the World Bank. Together these define the Investment Deficit Index. Per capital GDP reflects the capacity of individuals in a community to protect and respond to hazardous events. Aggregate GDP reflects the capacity to make large-scale protective infrastructure investments, and also potentially the incentive to protect valuable assets (e.g., developed urban areas). The Government Effective indicator reflects the ability of a delta community to utilize their GDP capacity in a way that potentially lowers risk.

Finally, relative sea level rise, estimated by the Anthropogenic Conditioning Index, acts to lower the overall elevation of the delta, bringing more people into the flood zone for any given hazardous event, and increasing the *exposure*, or number of people affected by flood conditions. Together, these three indexes define a risk space, identifying deltas where risk is increasing more or less rapidly due to relative sea level rise (Figure 2).

Risk in the Mekong, in Quadrant IV, is changing only moderately, primarily due to relatively low hazardous events. In the Amazon, despite much higher hazardous events than the Mekong, risk is also changing only moderately, due to low Anthropogenic Conditioning. In the Ganges however, the hazardous events are similar to the Amazon, but the Anthropogenic Conditioning is much higher, suggesting high relative sea level rise, and a rapid increase in risk. These estimates are on a per capita risk basis, when considering aggregated risk across the whole delta population, the Ganges has by far the highest rate of change of risk due to the very high population.

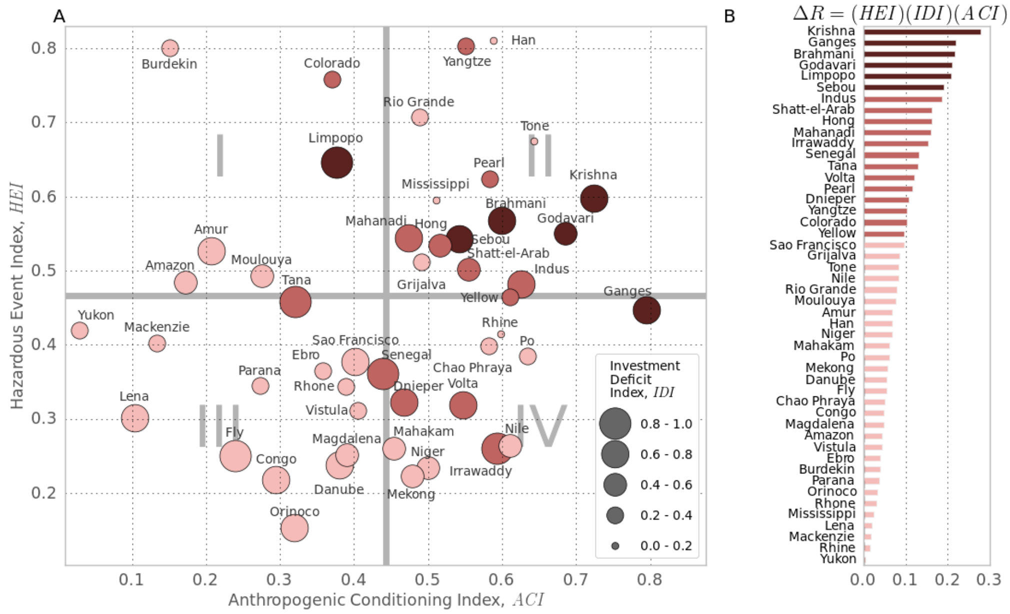


Figure 2. Delta risk space. HEI is the Hazardous Events Index, IDI is the Investment Deficit Index, and ACI is the Anthropogenic Conditioning Index.

These risk estimates can be considered as a delta's sensitivity to changes in relative sea level. However, this sensitivity is not static. The physical and socio-economic characteristics of deltas are expected to change in the future due to climate change, population growth, technological change, and economic trends. We have examined the influence of economic change on delta risk sensitivity to relative sea level rise. Currently, wealthy nations are able to reduce risk by improved infrastructure, captured in the Investment Deficit Index. According to the US Energy Information Administration, the average global cost of energy is expected to increase faster than global GDP through the middle of the 21st century. This effectively makes large, energy intensive infrastructure projects more expensive. Deltas that rely on infrastructure investments for risk-reduction, such as the Mississippi and the Rhine, will either have to invest greater amounts of money to maintain their lower risk, or maintain their level of spending but accept a higher levels of risk (Figure 3). This work has been published in *Science* (Tessler et al., 2015).

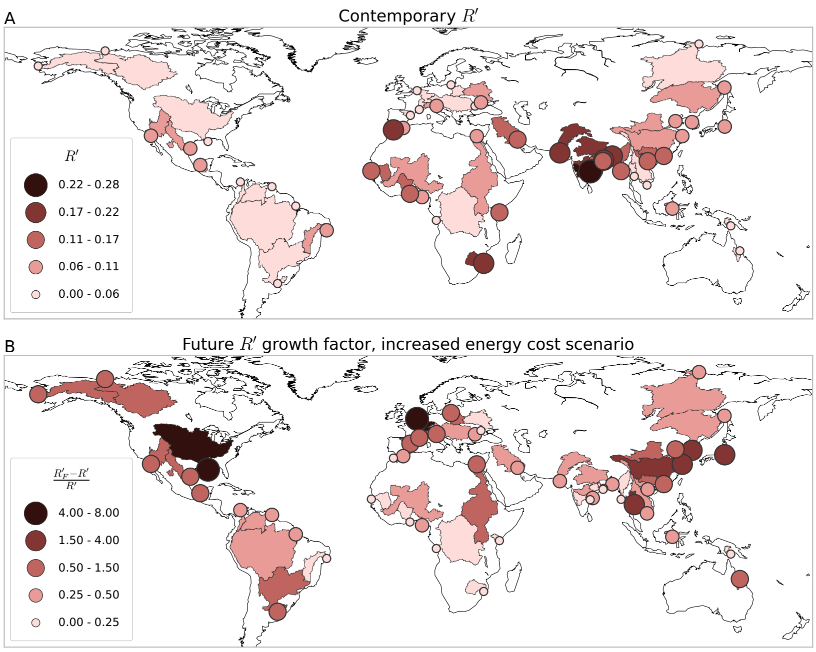


Figure 3. Contemporary and future risk based on increased energy cost secenario.

2. Environmental Stress Typology

In addition to utilizing the environmental indicators to quantify changes in delta risk, we have also worked to develop tools to assess common modes of environmental stress across deltas. This work is aimed at improving the efficacy of best-practice sharing across deltas, by identifying which systems are more are less similar to each other. We utilize several clustering algorithms to define relative closeness between deltas, and also identify which environmental indicators are most responsible for the close relationship. The results presented here are from a K-Means ($k=8$) clustering (Figure 4).

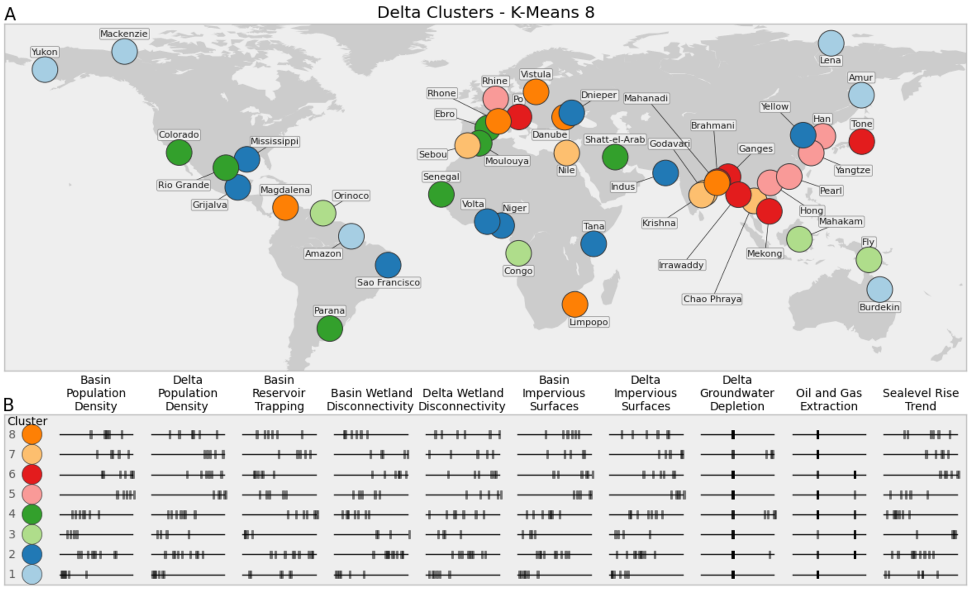


Figure 4. Global environmental stress clustering of deltas.

The Amazon is in Cluster 1 (Figure 4, light blue), along with the Amur, Burdekin, Lena, Mackenzie, and Yukon. These systems are all relatively low-stress. The Mekong and Ganges are both in Cluster 6 (Figure 4, dark red), with the Brahmani, Irrawaddy, Po, and Tone. These systems are moderately-to-highly stressed over nearly all indicators, with the exception of low-to-moderate levels of artificial upstream reservoirs and unsustainable groundwater extraction within the delta.

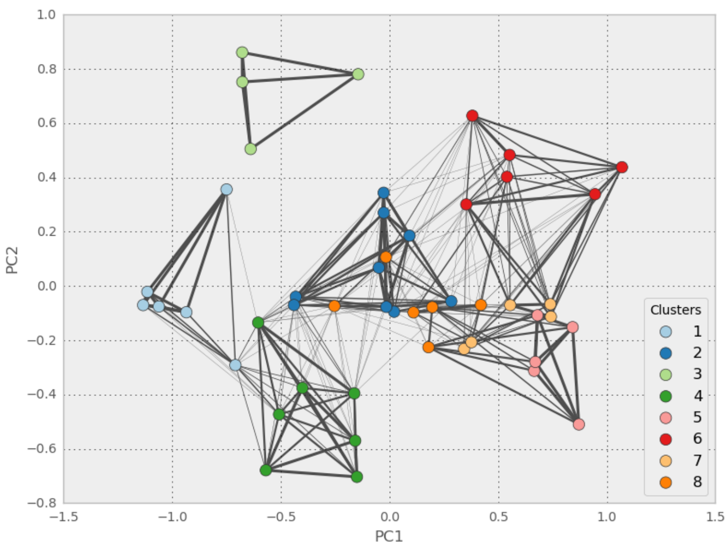


Figure 5. Global delta clusters, projected into the first two PCA components. Colors indicate KM8 cluster for a given delta, and line weight indicates the number of alternate cluster algorithms that assign two nodes to the same cluster.

By examining several different clustering algorithms, we have assessed the stability and robustness of each of the clusters (Figure 5). Low-latitude, low-population deltas in cluster 3 (Figure 5, light green) are distinct from other delta clusters. This work has been published in *Sustainability Science* (Tessler et al., 2016).

3. Coastline change detection and process attribution in the Mekong River Delta

Based on earlier risk results, we have identified the Mekong River Delta as a moderately at-risk delta with respect to relative sea-level rise. A moderate-to-densely populated delta, it does not currently have a high number of upstream dams and reservoirs. However, several projects are under construction or planned, particularly in the far upstream portions of the watershed. We have begun a study of the historical stability of the Mekong coastline using an approximately 25-year Landsat satellite imagery record. The observation results are being augmented with numerical modeling of the sediment flux and offshore aggradation and erosion of sediment to better understand the contemporary process that control coastline stability, and potential areas of concern given expected reductions in fluvial sediment and sea-level rise.

Landsat imagery was preprocessed to construct a composite image spanning the delta extent and consisting only of cloud- and shadow-free pixels for the years 1995, 2000, 2010, and 2015. Each image was based on two years of raw Landsat scenes. Clouds within each scene were masked using the Fmask algorithm (Zhu & Woodcock, 2012), and multiple observations of individual pixels were composited by averaging the 40th, 50th, and 60th percentiles of each band. This process discarded the highest and lowest observations, and the averaging removed some of the time-varying noise, such as offshore sediment plumes. Land and water regions of the composite image were estimated through supervised classification, and the coastline was extracted as the boundary of the largest land regions. Rates of erosion or aggradation between coastlines for each year were estimated using the Digital Shoreline Analysis System (Figure 6).

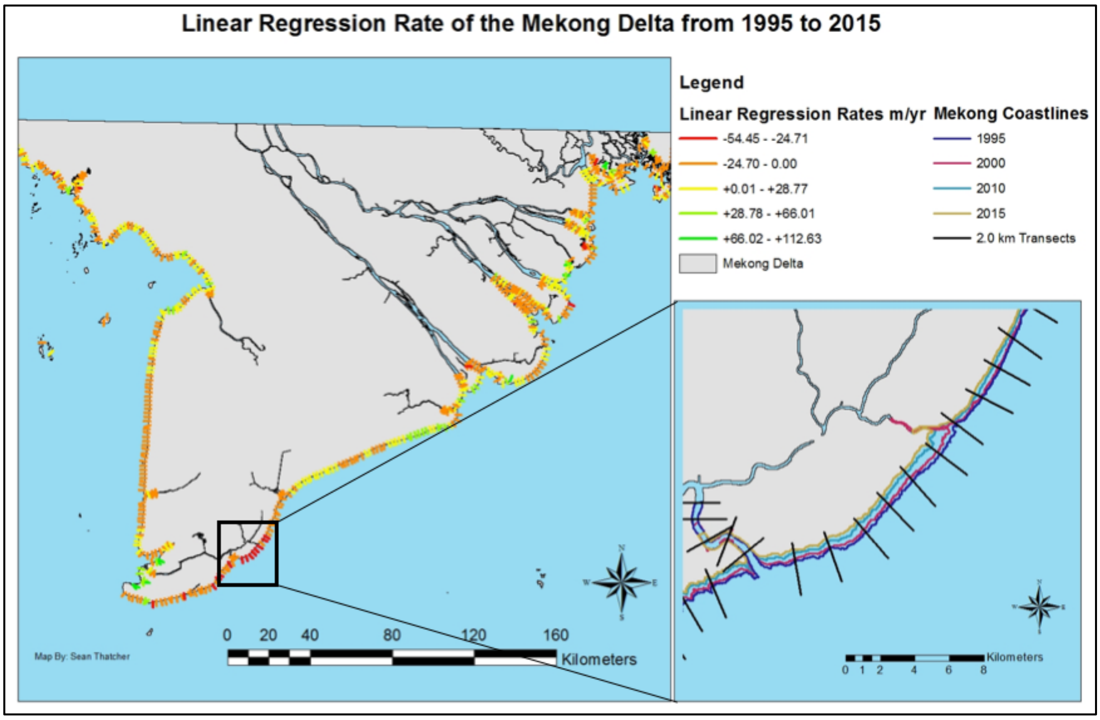


Figure 6. Linear erosion or aggradation rates of the Mekong River Delta coastline, estimated from 1995, 2000, 2010, and 2015 coastline positions

To investigate the major fluvial and coastal processes that influence the coastline migration rate, we have constructed a coastal ocean model based on COAWST, which couples the ROMS hydrodynamic model, the SWAN waves model, and a sediment model. Boundary conditions are provided by a global HYCOM simulation and WAVEWATCH III global wave model. Atmospheric surface forcing is from the ERA-Interim reanalysis. River discharge and sediment fluxes are estimated by the WBMplus river model. Preliminary modeling results showing one year of sediment deposition and erosion on the seafloor are shown in Figure 7. Areas of high erosion rates observed from Landsat imagery correspond to areas of high submarine erosion. Observed aggradation areas near the river mouths and along the south-eastern portion of Ca Mau Peninsula are also observed in the model.
This work is currently in preparation for publication.

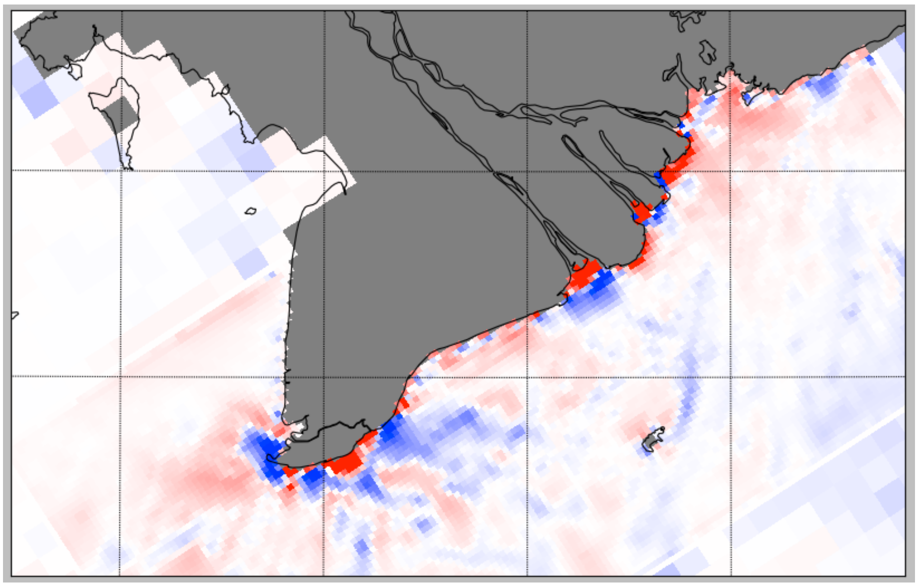


Figure 7. COAWST model of the Mekong Delta coastal zone. Red indicates areas of sediment aggradation, blue shows areas of sediment erosion. Results are from a 14-month simulation from November 2005-December 2006.

Additional Efforts:

International Workshop on Sustainable Deltas in NYC, September 2016

We are currently preparing to host a meeting in NYC for members of the Belmont-Forum DELTAS project, as well as a number of regional collaborators and participants in the regional workshops previously convened by BF-DELTAS project PIs. The workshop will run from September 12 through September 15. The first two days will focus on comparing and contrasting the results of the regional workshops, while the second half of the meeting will include presentation of research results from project members, synthesis of overall project achievements, and planning for next steps from research, data, and organizational perspectives.

Future Research (2016-2017)

In the next year our research focus will include

1. Complete analysis of Landsat-based coastline migration.
2. Extend coastal modeling analysis to include multiple years in order to asses annual variability of deposition and erosion rates.
3. Incorporate future scenarios of dam construction, land subsidence, and sea-level rise in coastal modeling
4. Continue earlier work investigating inundation processes on the Mekong delta, including land cover analysis and wetland dynamics assessment, and downscaling of previously-developed coarse inundation product (SWAMPS).

Publications

Brondizio ES, Foufoula-Georgiou E, Szabo S, Vogt N, Sebesvari Z, Renaud FG, Newton A, Anthony E, Mansur AV, Matthews Z, Hetrick S, Costa SM, Tessler ZD, Tejedor A, Longjas A, (2016), Catalysing action towards the sustainability of deltas, *Current Opinion in Environmental Sustainability*, *19*, 182-194. doi: 10.1016/j.cosust.2016.05.001.

Szabo S, Brondizio E, Hetrick S, Renaud FG, Nicholls RJ, Matthews Z, Tessler ZD, Tejedor A, Sebesvari Z, Foufoula-Georgiou E, Costa S, Dearing JA. (2016), Population dynamics, delta vulnerability and environmental change: Comparison of the Mekong, Ganges-Brahmaputra and Amazon delta regions, *Sustainability Science*, doi: 10.1007/s11625-016-0372-6.

Sebesvari Z, Renaud FG, Hass S, Tessler ZD, Kloos J, Szabo S, Vogt N, Tejedor A, Brondizio E, Kuenzer C (2016), A review of vulnerability indicators for deltaic social-ecological systems, *Sustainability Science*, doi: 10.1007/s11625-016-0366-4.

Tessler ZD, Vörösmarty CJ, Grossberg M, Gladkova I, Aizenman H, (2016), A global empirical typology of anthropogenic drivers of environmental change in deltas, *Sustainability Science*, doi: 10.1007/s11625-016-0357-5.

Schroeder R, McDonald KC, Chapman B, Jensen K, Podest E, Tessler ZD, Bohn TJ, Zimmermann R, (2015), Development and Evaluation of a Multi-Year Fractional Surface Water Data Set Derived from Active/Passive Microwave Remote Sensing Data, *Remote Sensing*, *7*, 16688-16732. doi:10.3390/rs71215843.

Tessler ZD, Vörösmarty CJ, Grossberg M, Gladkova I, Aizenman H, Syvitski JPM, Foufoula-Georgiou E., (2015), Profiling Risk and Sustainability in Coastal Deltas of the World, *Science*, *349* (6248), 638-643. doi:10.1126/science.aab3574.

Presentations

Tessler ZD, Vörösmarty CJ, Grossberg M, Gladkova I, Aizenmann H, Syvitski J, Foufoula-Georgiou E. From relative sea level rise to coastal risk: Estimating contemporary andfuture flood risk in deltas. CSDMS Annual Meeting, Boulder, CO, May 19, 2016.

Tessler ZD, Vörösmarty CJ, Grossberg M, Gladkova I, Aizenmann H, Syvitski J, Foufoula-Georgiou E. The geophysical, anthropogenic, and social dimensions of delta risk: Estimating contemporary and future risks at the global scale. AGU Fall Meeting, San Francisco, CA, December 17, 2015.

Jensen K, McDonald KC, Schroeder R, Tessler ZD. Bridging the past with today’s microwaves remote sensing: A case study of long term inundation patterns in the Mekong River Delta. AGU Fall Meeting, San Francisco, CA, December 18, 2015.

Workshops and Conference Sessions

Deltas and sea-level rise: geological and social-ecological perspectives. Co-conveners: Céline Grall, Anjali M Fernandes, Zachary D Tessler, Carol Wilson. Session GC002, AGU Fall Meeting, San Francisco, CA, 12-16 December 2016.

Steven Goodbred

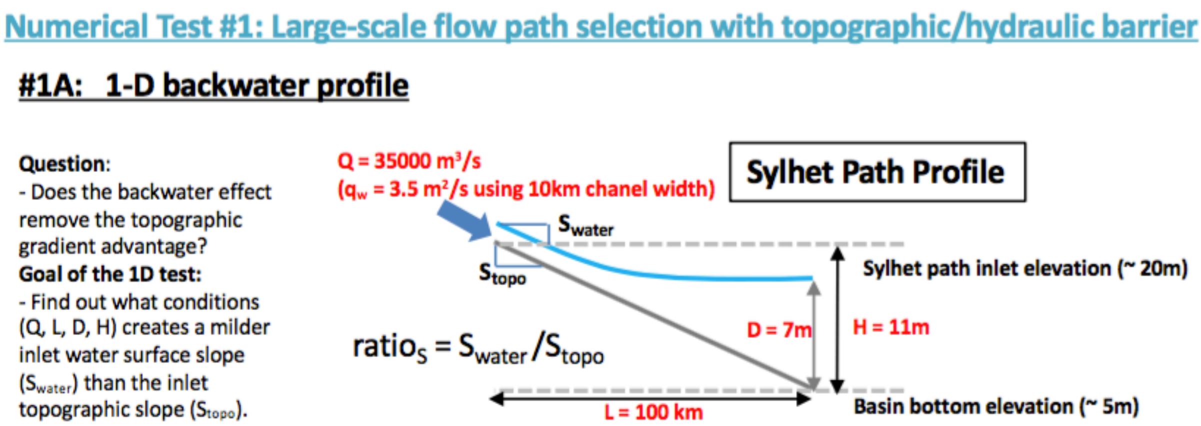
Vanderbilt University

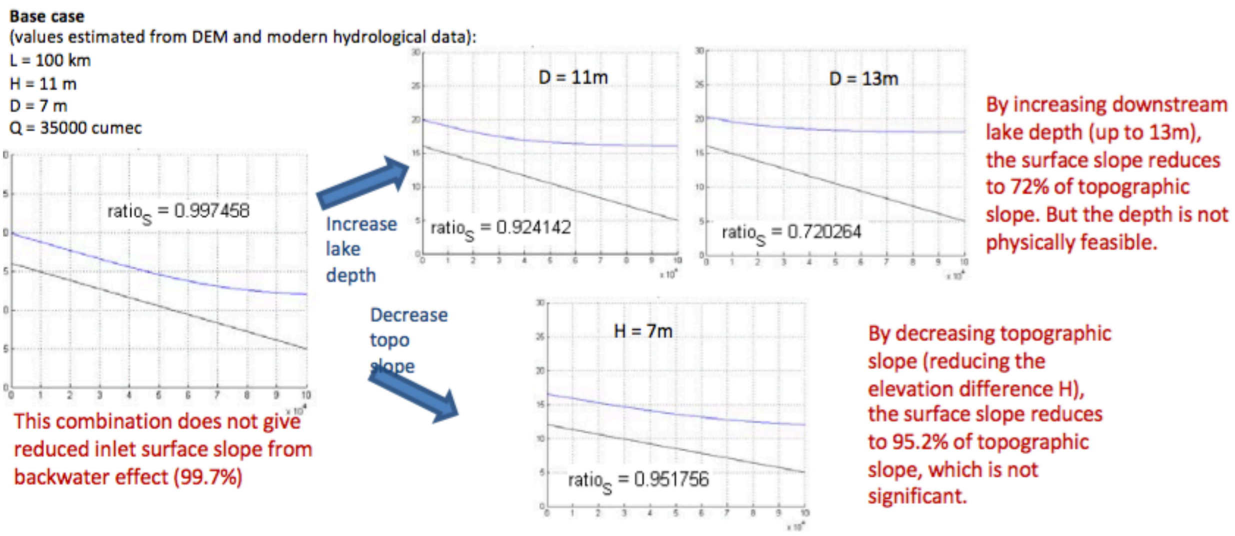
Research Themes and Accomplishments during 2015-2016

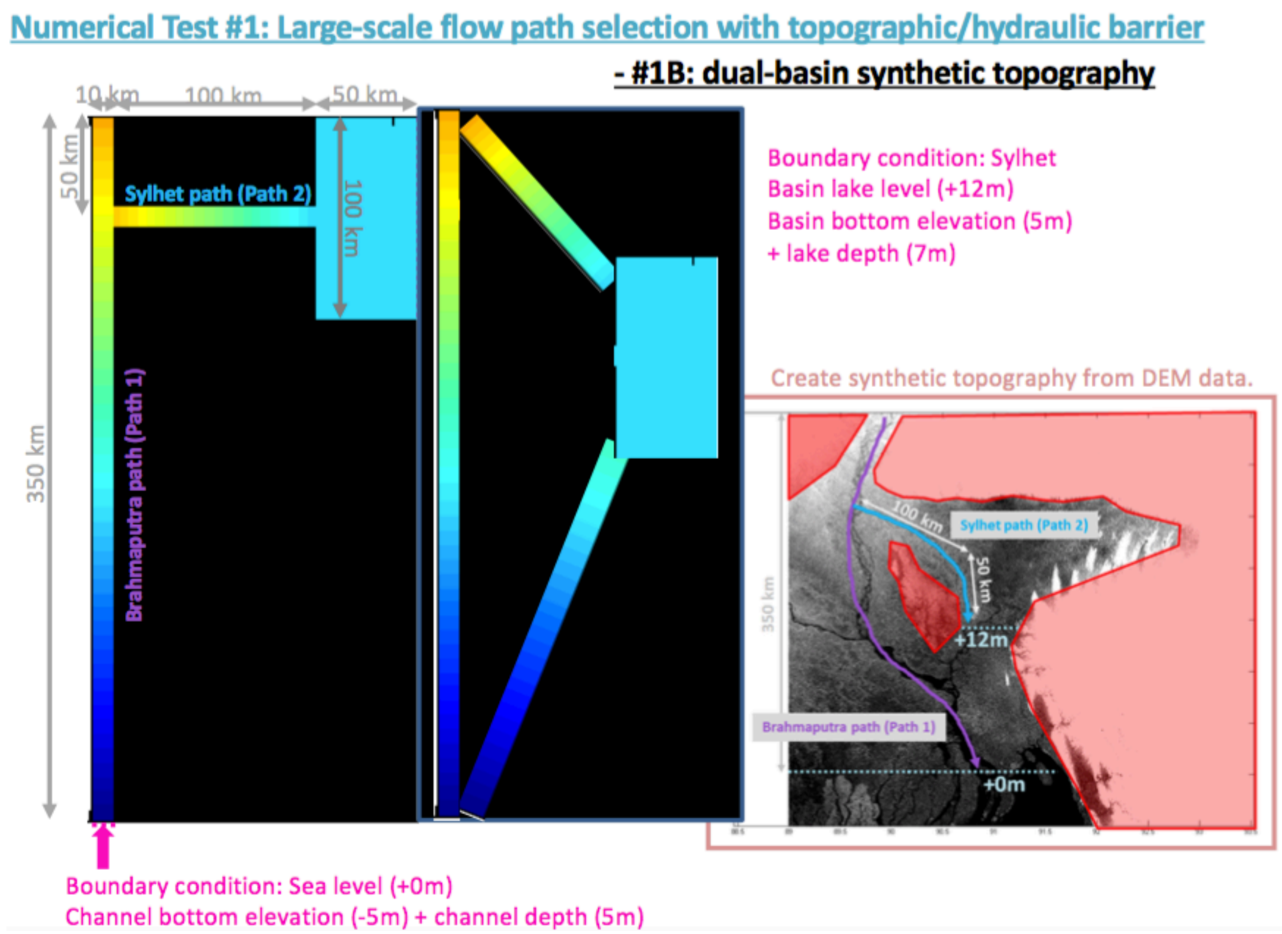
All major activities reported for 2014 have continued through the past year, with emphasis on data analysis and writing of manuscripts. Several of these are nearing submission and reported in the products section. In addition to ongoing field observations and related research, the project established a new phase of research that couples the earlier field efforts with quantitative modeling approaches. This has taken place through a new subcontract established with Paola Passalacqua at University of Texas, Austin to support post-doctoral fellow Man Liang, as described below.

1. Model scenarios exploring various hypotheses about the Ganges-Brahmaputra-Meghna delta (GBMD) behavior

Major results from this year's efforts include the completion of multiple model scenarios that explore various hypotheses about GBMD behavior. Specifically, what role does internal delta-floodplain hydrology plays in controlling river path selection and avulsion patterns. Results from these exercises are summarized in the following figures, with results being prepared for publication.

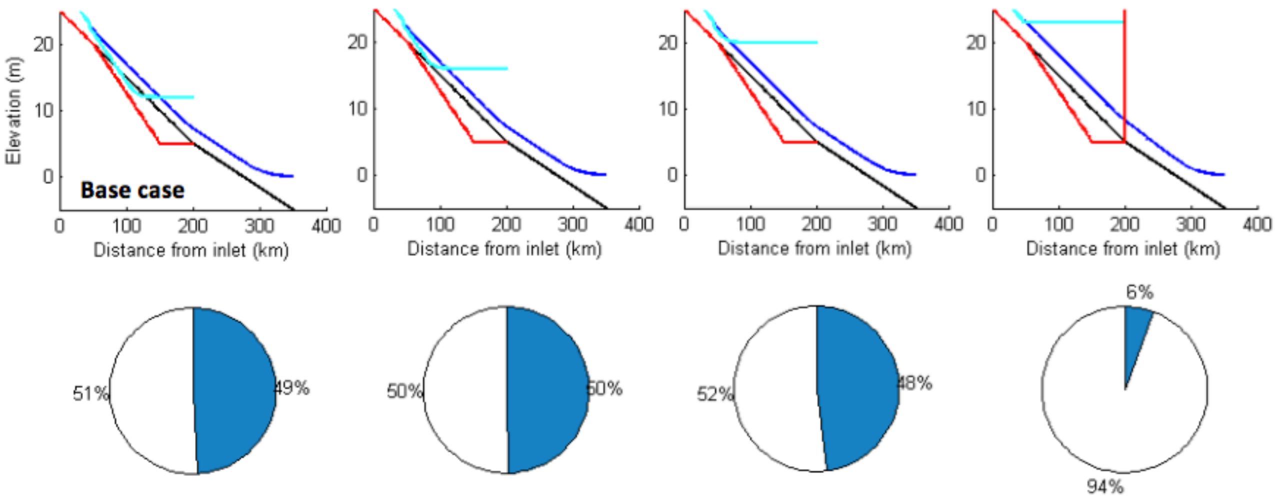



Base case
(values estimated from DEM and modern hydrological data):
L = 100 km
H = 11 m
D = 7 m
Q = 35000 cumec
ratio_S = 0.997458
This combination does not give reduced inlet surface slope from backwater effect (99.7%)
Increase lake depth
D = 11m
ratio_S = 0.924142
D = 13m
ratio_S = 0.720264
By increasing downstream lake depth (up to 13m), the surface slope reduces to 72% of topographic slope. But the depth is not physically feasible.
Decrease topo slope
H = 7m
ratio_S = 0.951756
By decreasing topographic slope (reducing the elevation difference H), the surface slope reduces to 95.2% of topographic slope, which is not significant.

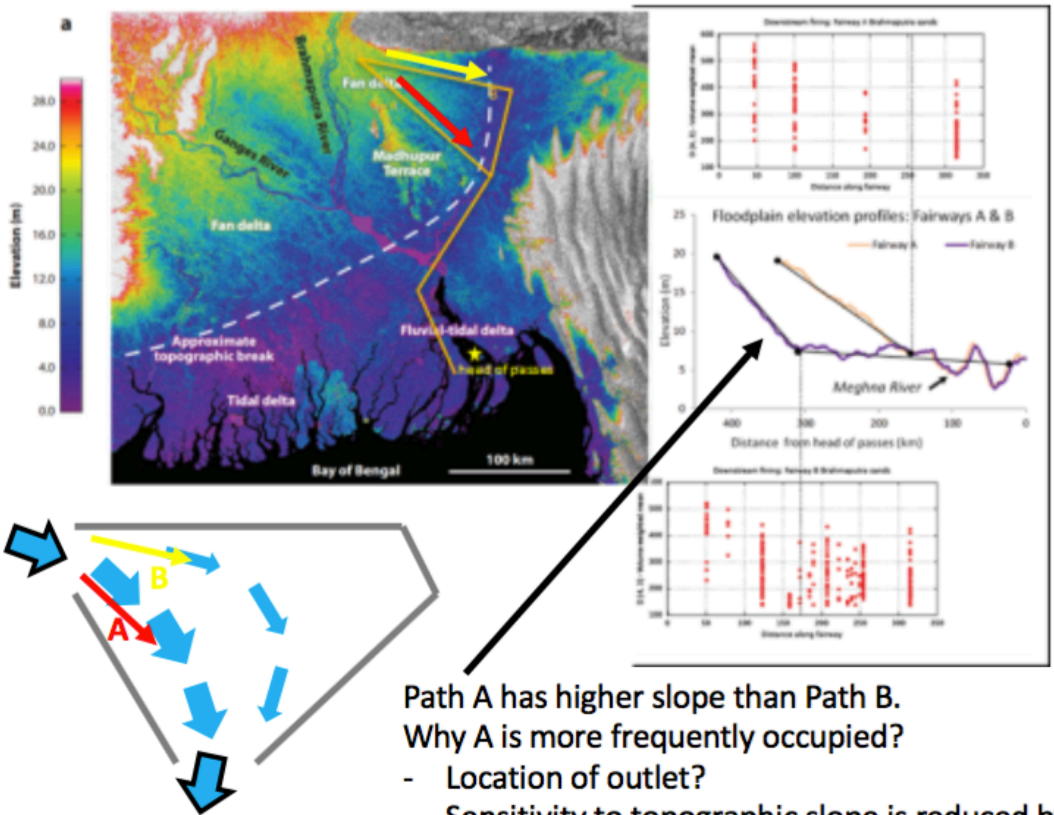

Numerical Test #1: Large-scale flow path selection with topographic/hydraulic barrier
- #1B: dual-basin synthetic topography
10 km
100 km
50 km
50 km
100 km
350 km
Sylhet path (Path 2)
Brahmaputra path (Path 1)
Boundary condition: Sylhet Basin lake level (+12m)
Basin bottom elevation (5m) + lake depth (7m)
Create synthetic topography from DEM data.
100 km
Sylhet path (Path 2)
50 km
+12m
Brahmaputra path (Path 1)
+0m
Boundary condition: Sea level (+0m)
Channel bottom elevation (-5m) + channel depth (5m)

- #1B: dual-basin synthetic topography

Increase lake depth

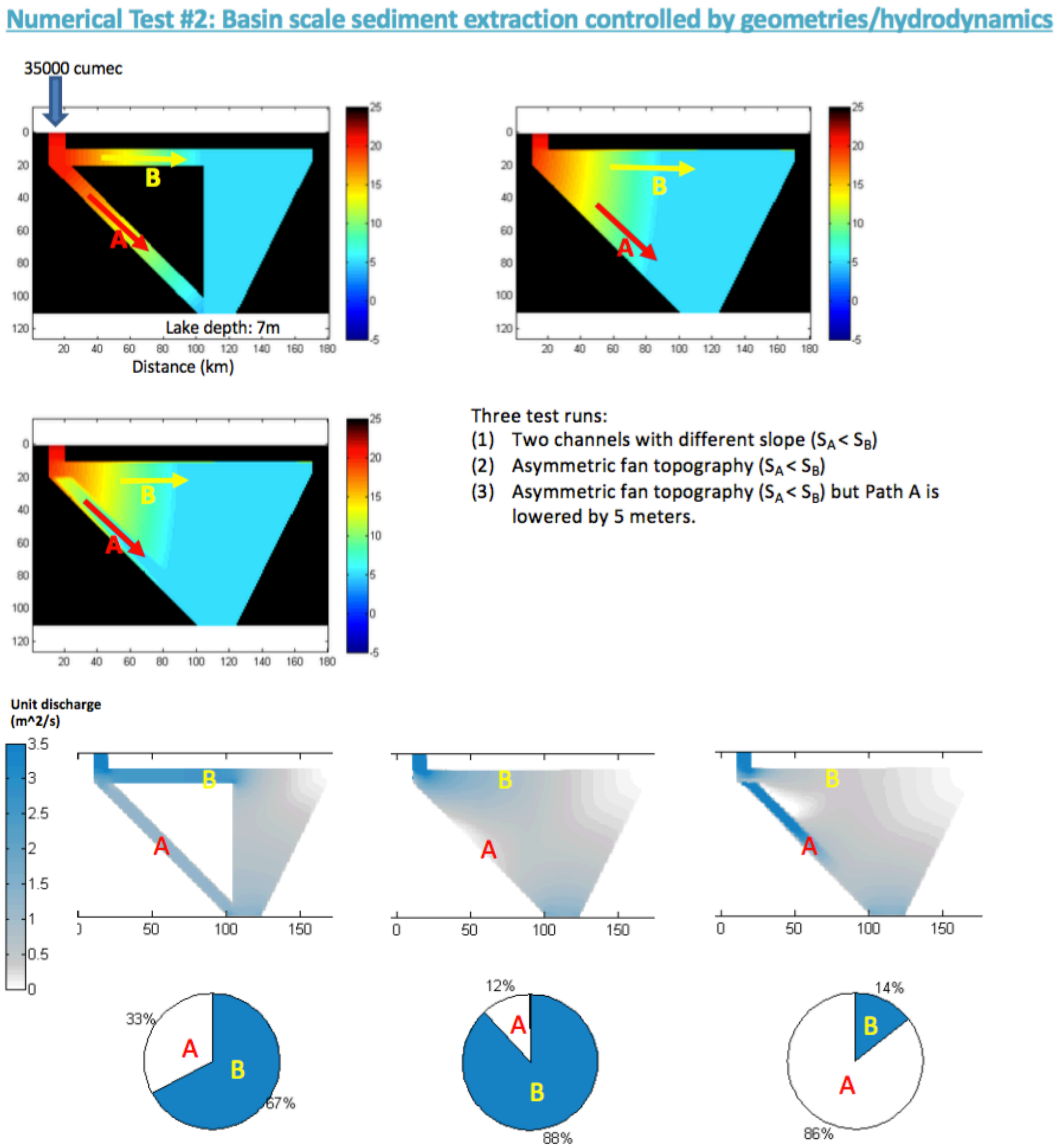


Similar to the 1-D profile tests, by increasing downstream lake depth, flow preference does not happen until extreme high lake level (almost as high as the water surface elevation at the bifurcation point). Therefore backwater effect alone is not able to produce flow preference to path 1 (main Brahmaputra path) given the distance, discharge, and topographic slope combination.



Path A has higher slope than Path B.
Why A is more frequently occupied?

- Location of outlet?
- Sensitivity to topographic slope is reduced by backwater?



Location of outlet does not introduce preference of path A, which has a smaller topographic slope. However, by making path A significantly deeper (2x the depth of path B), flow strongly prefer path A.

2. Linking Surface Processes to Subsurface Architecture with Reduced-Complexity Modeling

Environmental controls such as tectonics and sediment supply act on the fluvial organization and result in a wide range of subsurface patterns. Predicting subsurface architecture from surface processes, or deriving past conditions and surface dynamics from sedimentary record, remains difficult due to the lack of understanding on how the self-organization of deltaic channels respond to external controls and how their response is preserved in the stratal architecture. Recent work on the Ganges-Brahmaputra-Jamuna (GBJ) Delta system has shown a strong evidence of the linkage between delta surface network and the stratigraphic record (Passalacqua et al., 2013, Wilson et al., 2015). Many questions remain un-answered about this delta, which is among the most dynamic morphological systems in the world, such as the flow path selection of rivers and the deposition pattern of sediments.

The objective of this research is to explore the conditions that lead to changes in the behavior of channel networks and what signatures are preserved in the sedimentary record. Specifically, we will start with a case study on the historical channel occupations of Sylhet Basin and investigate the relative effects of basin topography and differential subsidence. A series of numerical tests will be carried out using a reduced-complexity channel-resolving model for delta formation (Liang et al., 2015a, 2015b), to simulate a range of subsidence rates and topographic depression in the setup of Sylhet Basin, aiming at reproducing the subsurface structure composed from the core samples, therefore providing insights to the morphological history of the system. In the next stage, we plan on expanding the modeling framework to include more key processes to the GBJ system such as tidal forcing, so that a comprehensive linkage between surface processes and subsurface structure can be achieved.

3. New collaborative NSF Coastal SEES project involving Belmont co-PIs Goodbred(Vanderbilt) and Overeem (Colorado), plus former Belmont post-doc Carol Wilson (LSU) and Belmont sub-contract Paola Passalacqua (UT Austin).

One major outcome of the Belmont Forum DELTAS project has been the development and successful funding of a new collaborative NSF Coastal SEES project involving Belmont co-PIs Goodbred(Vanderbilt) and Overeem (Colorado), plus former Belmont post-doc Carol Wilson (LSU) and Belmont sub-contract Paola Passalacqua (UT Austin). The project is titled *Coastal SEES Collaborative Research: Multi-scale modeling and observations of landscape dynamics, mass balance, and network connectivity for a sustainable Ganges-Brahmaputra delta* is a direct outcome of the collaboration developed via the Belmont Forum support. Following is the abstract describing the new work that builds on the Belmont DELTAS effort:

River deltas around the world are in a state of modest to severe decline, primarily in response to anthropogenic activities such as the damming of rivers, extensive embankment systems, groundwater and gas extraction, and intense land-use pressures. These settings are also among the world's most physically dynamic, being impacted by sea-level rise and subsidence, river flooding, channel erosion, and storms. Such vulnerabilities are further magnified in highly populated delta systems, notably the large mega-deltas that rim Asian coasts in politically sensitive regions from Pakistan to China. These environments suffer not only from having more humans, infrastructure, and livelihoods in peril, but also from the anthropogenic strain that large populations place on physical and ecological support systems. In Bangladesh and West Bengal, India, the Ganges-Brahmaputra-Meghna delta (GBMD) may well be the prime example as the world's largest and most densely populated delta system, hosting 150 million people in an area the size of Louisiana. In this Coastal SEES project, a diverse group of scholars with expertise across several earth-science and engineering disciplines are brought together to answer questions about the fate and future sustainability of the GBMD and its human population. Specifically, is there sufficient river sediment available for the delta to keep pace with sea-level rise to 2100? How does the delta's network of river and tidal channels effectively distribute water and sediment across the region? How are human activities affecting this channel-network system, and what are the subsequent repercussions on human infrastructure? How can research-based knowledge developed in response to these questions help with planning and decision making for a sustainable GBMD and deltas elsewhere?

To address these questions, the project combines innovative quantitative tools (numerical modeling, network and connectivity analysis) with new and existing observational data to analyze the coupled human-natural system and long-term sustainability of the GBMD. Specifically, team members will (i) develop a detailed mass balance for delta-wide sediment dispersal; (ii) quantitatively analyze the connectivity of the delta-system network that disperses this sediment; (iii) integrate this knowledge through numerical modeling at local to global scales; (iv) use observational data of landscape and channel dynamics to understand coupled land-sea interactions; (v) evaluate the quality of regional soil and water resources and their links with physical and anthropogenic processes; (vi) assess the impact of these delta dynamics on the human environment and transportation, and finally (vii) disseminate this knowledge through a variety of educational activities and opportunities for students, researchers, and professionals. Team members have collaborated extensively with local entities and universities in Bangladesh; through these contacts the knowledge developed in this project will reach relevant stakeholder communities. Findings are especially urgent to guide large-scale engineering efforts underway to improve the Bangladesh coastal-zone stability. Final products will provide a grounded, integrated, and multidisciplinary view of how the world's largest delta works and its plausible responses to environmental change in the coming century.

Future Research (2016–2017)

Two principal goals for the coming year (now on first-year NCE) will be (a) to complete and submit several in progress manuscripts and (b) work with large Belmont Forum DELTAS team for integrated science results across.

Publications 2015-2016 (partially funded by this grant)

Md. R., and Akter, F., (2016), Sources of salinity and arsenic in groundwater in southwest Bangladesh, *Geochemical Transactions*, *17*:4 (doi:10.1186/s12932-016-0036-6).

Benneyworth, L., Gilligan, J., Ayers, J., Goodbred, S., George, G., Carrico, A., Karim, Md. R., Akter, F., Fry, D., Donato. K., Piya, B. (2016), Drinking water insecurity: water quality and access in coastal south-western Bangladesh. *International Journal of Environmental Health Research*, 1-12 (DOI:10.1080/09603123.2016.1194383).

Worland, S.C., Hornberger, G.M., Goodbred, S.L. (2015), Source, transport, and evolution of saline groundwater in a shallow Holocene aquifer on the tidal deltaplain of southwest Bangladesh, *Water Resources Research*, *51*(7): 5791-5805, doi:10.1002/2014WR016262

Auerbach, L.W., Goodbred Jr, S. L., Mondal, D.R., Wilson, C.A., Ahmed, K.R., Roy, K., Steckler, M.S., Small, C., Gilligan, J.M., Ackerly, B.A. (2015), Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain, *Nature Climate Change, 5*(2): 153-157.

Wilson, C.A. and Goodbred, Jr., S.L., (2015), Building a large, tide-influenced delta on the Bengal margin: Linking process, morphology, and stratigraphy in the Ganges-Brahmaputra delta system, *Annual Review of Marine Science, 7*: 67-88.

Conference presentations and abstracts:

Bain, R. Goodbred, S., Hale, R., Reed, M., Best, J. Hydrodynamic Properties of a Large Tidal Channel on the Ganges-Brahmaputra Delta, Bangladesh, with Implications for Channel Morphology and Sediment Transport. AGU National Meeting, San Francisco, CA. December

14-18, 2015.

Goodbred, S., Pickering, J., Wilson, C., Sincavage, R., Steckler, M., Akhter, S., Grimaud, J-L., Hossain, S., Kuehl, S, Mondal, D., Palamenghi, L., Paola, C., Schwenk, T., Spiess, V., Ullah, Md.S. Embracing Non-Stationarity – Hysteresis and Coherence in the Ganges-Brahmaputra Source-to-Sink System and Its Imprint on the Stratigraphic Record. AGU National Meeting, San Francisco, CA. December 14-18, 2015. (**INVITED**)

Hale, R., Goodbred, S., Bain, R., Wilson, C., Reed, M., Best, J. River discharge controlling a tidal delta: the interplay between monsoon input and tidal reworking in SW Bangladesh. AGU National Meeting, San Francisco, CA. December 14-18, 2015.

Patrick, M., Goodbred, S., Gilligan, J, Tasich, C., Hossain, S. and Ahmed, KM. Stratigraphic Evolution of the Ganges-Brahmaputra Lower Delta Plain and its Relation to Groundwater Arsenic Distributions. AGU National Meeting, San Francisco, CA. December 14-18, 2015.

Sincavage, R., Goodbred, S., Wilson, C., Pickering, J., and Paola, C. Mass balance, bedload extraction, surface morphology, and Holocene stratigraphic architecture along distinct sediment transport pathways of the Brahmaputra River in Bengal Basin. AGU National Meeting, San Francisco, CA. December 14-18, 2015.

Wilson, C., Goodbred, S., Sams, S., and Small, C., Anthropogenic changes to the tidal channel network, sediment rerouting, and social implications in southwest Bangladesh. AGU National Meeting, San Francisco, CA. December 14-18, 2015.

Wilson, C., Goodbred, S., Sincavage, R., Steckler, M., and Pickering, J. Linking process, morphology, and stratigraphy in the Ganges-Brahmaputra-Meghna delta. AGU National Meeting, San Francisco, CA. December 14-18, 2015.

INDIANA UNIVERSITY

Eduardo Brondizio, Nathan Vogt, Scott Hetrick, Andressa Vianna Mansur, Samapriya Roy

Indiana University

Research Themes and Accomplishments during 2015-2016

The Indiana University team dedicated the third year of the project to accomplish the following goals:
1-conclude the Deltas-DAT system for the Amazon delta region: completed.
2-develop a system for data sharing of the Amazon Deltas-DAT: partially completed.
3-develop and publish a social-ecological systems framework for the analysis of delta systems, using the Amazon region as example: completed.
4-complete analysis of urban vulnerability to flooding for 41 cities in the region: completed.
5-develop an analysis of adaptation strategies by urban residents presenting different socioeconomic conditions and risk of flooding: on-going.
6-carry out spatial analysis of urban vulnerability (see item 4) to identify spatial autocorrelation and clustering associated with urban expansion and infrastructure development: on-going.
7-develop and publish a synthesis articles with project collaborator to identifying advances and new areas for research and collaboration: completed.
8-carry out a second round of stakeholder workshops in the Amazon delta, including meetings in 5 localities representative of the social and biophysical diversity of the region: completed.

1. Highlights

In Mansur et al., 2016 An Assessment of Urban Vulnerability in the Amazon Delta and Estuary: A multi-Criterion Index of Flood Exposure, Socio-Economic Conditions and Infrastructure we developed an analytical framework to define socio-economic vulnerability in the urban ADE, we applied a composite index based in three dimensions of vulnerability: flood exposure, socio-economic sensitivity and infrastructure. The index combines data from public databases at the most disaggregated level of analysis of census data (n = 2938 census sectors) and uses a methodology based on data from Shuttle Radar Topography Mission (SRTM) to assess and characterize sectors based on their flood risks. Results indicate that over 60% of the urban sectors within the AD present high degree of vulnerability, reaching a population of over 1 million inhabitants. This degree vulnerability will define and reiterates the impacts of future climate changes across society and as it extends beyond the urban areas of the Amazon Delta.

In Szabo et al., 2016 Population dynamics in the context of environmental vulnerability: Comparison of the Mekong, Ganges-Brahmaputra and Amazon delta regions we provide overview of the demographic trends in the Mekong, Ganges-Brahmaputra and Amazon deltas. Results reflect a similarity with the national trends, with shifts in population structure that results in aging populations, which will increase the demand for provisioning of care and labor supply. Trends in fertility combined with life expectancy suggest that population in delta regions are likely to stabilize or decline.

Rural–urban population distribution is likely to continue to change across the three deltas as rural families seek employment opportunities and better services in urban area, however circulation of people and resources will continue to shape the economy and governance of rural sectors. Environmental threats are more likely to affect population, thus efficient policy planning and progress toward social and ecological sustainability will be crucial in delta regions.

In Vogt et al. 2016 Local Ecological Knowledge and Incremental Adaptation to Changing Flood Patterns in the Amazon Delta we documented the multiple functions and roles of local ecological knowledge of expert farmer-fishers in the Amazon Delta in helping local populations to adapt to changes in flood patterns and non-climatic pressures. We documented how local ecological knowledge used to adapt the spatial configuration and composition of their land/resource use systems (agro-diversity) and their produced and managed resources (agro-biodiversity) at landscape, community and household levels. We found that this ecological knowledge, accumulated over generations, facilitated a process of incremental adaptation to increasing hydro-climate and market stresses and shocks. The results suggest that expert farmer-fishers maintain knowledge of how to reintroduce and reconfigure individual products, communities of products, and land-use types across the aquatic, floodplain and upland ecologies of the Delta. They rarely respond to new market opportunities or a climate shock by whole-sale conversion from one mono-crop to another that would make their landscapes and livelihoods more vulnerable. We found local ecological knowledge should be included in strategies to build resilience of deltas to climate changes.

In addition to publications in academic journals, we have contributed to the publication of a brief for policy makers (see Sebesvari et al., 2016, publication related to Deltas and the Sustainable Development goals).

2. Stakeholder Consultation Workshops

One of the key activities of the project during this year was the coordination of five stakeholder consultation workshops in the Amazon delta. Based on a review of existing vulnerability frameworks and indicators, current and future risks, their probability and urgency, as well as current adaptive capacities, a list of vulnerability indicators was co-developed with local stakeholders in three globally significant delta systems: the Ganges-Brahmaputra-Meghna (GBM), the Mekong, and the Amazon in collaboration with regional experts delta regions. The consultation for the Amazon Delta took place in Belém in May 2015 and May 2016. During facilitated discussions in 2015, invited participants (representatives of sectoral agencies, scientists, and nongovernmental organizations) discussed current pressures and impacts as well current and future vulnerabilities of the social-ecological system in place. Based on the outcome of the discussion, participants developed a set of indicators to be used in delta risk and vulnerability assessments. Using and critically assessing the developed indicators combined with a scientific review on indicators, a final set of indicators was developed and used for an assessment by the team in the United Nations University in Germany. In parallel, we also conducted a scientific assessment of vulnerability in the urban Amazon Delta. In May 2016, representing the BF-Deltas project group, MSc Andressa Mansur presented the results of the risk and vulnerability assessments for the Amazon delta to different stakeholders in four cities within the Amazon Delta: Belém, Macapá, Soure and Gurupá. The stakeholder meetings allowed us to collect targeted feedback and occasionally also additional data for the construction of the GDVI (Global Delta Vulnerability Index) and other collaboration papers, such as the adaptive capacity of the city of Belém, and further a more detailed application of the GDVI for a regional case study only in the Amazon Delta in collaboration with project partners.

The stakeholder workshops carried out in the Amazon delta in May 2-10, 2016 provided an opportunity to share results and request feedback from a wide range of stakeholder groups. The stakeholder meetings were co-organized by The United Nations University, Institute for Environment and Human Security (UNU-EHS) – the project partner responsible for the project component Global Delta Vulnerability Index (GDVI) represented by Dr. Michael Hagenlocher and Dr. Zita Sebesvari, and MSc Andressa Vianna Mansur, Dr. Eduardo Brondizio (Indiana University)

And collaboration of local researchers, including:

- In Soure with local researcher: Vivian Zeidemann (UFPA – Federal University of Belém – Belém).
- In Belém – SIPAM: Ricardo Fialho (SIPAM – System for the Protection of the Amazon)
- In Macapá with local researcher: Luis Roberto Takiyama (IEPA - Institute for Scientific and Technological Research of the State of Amapá, Centre for Water Research – Macapá)
- In Gurupá with local researcher: Lucy Miller (PhD student in Anthropology at Indiana University)

Number of participants: 50 participants
Soure: 11 participants ; SIPAM-Belem: 7 participants ; Macapa: 13 participants; Gurupa: 5 participants; Belem: 14 participants

Main Topics
- Present the results of the risk and vulnerability assessments and its elements for the Amazon delta to different stakeholders,
- Discuss the outcomes, collect targeted feedback and occasionally also additional data for the construction of the GDVI (Global Delta Vulnerability Index) and other collaboration papers

Future Research (2016–2017)

A no cost extension has been requested for this project. Our main goals are:

1. To complete the data dissemination system that will make the Amazon Deltas-DAT available to the larger community. We are currently in conversation with the IEDA group at

Columbia University to finalize our data transfer and an interface for visualization and user access;
2. To complete and submit for publication the analysis of adaptation strategies of urban residents to flooding;
3. To complete and submit for publication the analysis of local perception of tidal change and how it correlates to hydrological changes measured in stations located upstream in the north and southern channels of the Amazon delta.
4. To prepare a new proposal to support the team in pursuing new research questions identified for instance in Brondizio et al 2016 (COSUST)

Book Chapters

Brondizio, E. S. (2015). Entangled Futures: Anthropology's engagement with global change research.. *Anthropology and Climate change: From encounters to action. 2nd.* S. Crate and M. Nuttall. Left Coast Press. Walnut Creek, CA.

Publications

Brondizio, E. S. (2016). The elephant in the room: Amazonian cities deserve more attention in climate change and sustainability discussions.. *ClimaCom Cultura Científica - Special issue Vulnerabilidade*. 2.

Brondizio, E. S. and F. M Le Tourneau (2016). Environmental Governance for All. *Science*. 352 .

Brondizio, E. S. and J. Syvitski (2016). The Anthropocene. *Special issue of Global Environmental Change: Human and Policy Dimensions*. 39 . DOI: doi:10.1016/j.gloenvcha.2015.09.017

Brondizio, E. S., A. C. B. de Lima, S. Schramski C. Adams (2016). Social and Health Dimensions of Climate Change in the Amazon: A Review. *Annals of Human Biology*. 43 (4).
Brondizio, E. S., K. O'Brien, X. Bai, F. Biermann, W. Steffen, F. Berkhout, C. Cudennec, M. C. Lemos, A. Wolfe, J. Palma- Oliveira, C-T. Arthur Chen (2016). Re-conceptualizing the Anthropocene: A Call for Collaboration.. *Global Environmental Change: Human and Policy Dimensions*.

Brondizio, E. S., N. Vogt, A. Mansur, S. Costa, E. Anthony, S. Hetrick (2016). A Conceptual Framework for Analyzing Deltas as Coupled Social Ecological Systems: An example from the Amazon River Delta and Estuary. *Sustainability Science*, doi: 10.1007/s11625-016- 0368-2

Brondizio, E. S. (). Conditional Cash Transfers, Food Security and Health: biocultural insights for poverty alleviation policy from the Brazilian Amazon. *Current Anthropology*.

Brondizio, E.S., E. Foufoula-Georgiou, S. Szabo, N. Vogt, Z. Sebesvari, F. G. Renaud, A. Newton, E. Anthony, A. V. Mansur, Z. Matthews, S. Hetrick, S. M. Costa, Z. Tessler, A. Tejedor, A. Longjas, John Dearing (2016). Catalyzing action towards the sustainability of Deltas. *Current Opinions in Environmental Sustainability.*

Mansur A.V., Brondízio E. S, Roy, S., Soares P. P. M., Newton, A. (). Climate change adaptation deficit in the largest city of the Amazon Delta: The case of Belém. *Regional Environmental Change*.

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Other Products

Software or Netware.
DeltaDat Master kml was created for easy dissemination of state wise data, the template can be modified in the future to fit further needs and appended easily

Data and Research Materials (e.g. Cell lines, DNA probes, Animal models).
Digital Globe Image Grant : Area of about 1000 square kilometer and grant value of over $17,000 for high resolution imagery over Belem

Curator of the exhibit.
"*Acai from local to global*" at the Mathers Museum of World Cultures, Indiana University. August 19, 2015 to April 31, 2016. Co-curator with Andrea D. Siqueira. Photographic panels and over a 100 items show the globalization of the acai palm fruit and its relationship to local populations, economy, and development in the Amazon. The Exhibit is part of the College of Arts and Sciences 'Themester' on 'food'. ~10,000 visitors

Lecture.
Brondizio, E. S. Studying complexity in the Amazon delta. Lecture presented at the Department of Geography, Geology, and Anthropology at Indiana State University, March 24, 2016 (4pm).
Lecture series. Brondizio, E. S. **Lecture Series**: *Bridging: Reflections on History, Scales, and Knowledge Systems in Human-Environment Research*. Presented at the Research Institute for Humanities and Nature (RIHN), Kyoto, Japan, June 2, 6, and 8, 2016.
Lecture 1: A cultural ecology of the Anthropocene: An anthropological perspective to the history of human-environment interaction research.
Lecture 2: A microcosmo of global change: Reflections on scale and complexity in the Amazon
Lecture 3: Bridging knowledge systems: A problem-oriented conceptual framework for social-ecological analysis

Seminar.
Brondizio, E. S. Seminar presented at the United Nations University Institute for Advanced Studies, Tokyo, Japan, June 10, 2016.
Workshop Organizer. Brondizio, E. S, [organizer]. *International Workshop on Social-Ecological Systems Frameworks: Experiences from the USA, Japan, and Brazil*. The Ostrom Workshop, Indiana University, April 18 2016. [30 participants].

Claudia Kuenzer's group

University of Wuerzburg

Benjamin Mack, Patrick Leinenkugel, Juliane Huth

Research Themes and Accomplishments during 2015-2016

Our research efforts over the past year have concentrated on 5 main areas: (1) Creation of high quality cloud/cloud-shadow free synthetic satellite image composites for the focus deltas; (2) Land use/land cover analysis in the Ganges Brahmaputra River Delta; (3) Dataset creation for coastline and river course change analysis; and (4) Land Use/Land Cover Classification in the Mekong River Delta with MODIS Time Series (5) River Deltas Animation.

Special emphasis was placed on the Mekong, Ganges Brahmaputra, and Amazon River Deltas (MRD, GBR, ARD), which are the focus deltas of the DELTAS project funded under Belmont Forum-G8 Collaborative Research. However, the developed methods and frameworks are generic and can be applied to other deltas, too.

1. Creation of high quality cloud/cloud-shadow free synthetic satellite image composites for the focus deltas

In the last report we described the processing chain developed for automatically processing large amounts of Landsat data, which became available with the opening of the USGS Landsat archive. Automatic mass processing capabilities are important for deriving spatially consistent cloud/cloud shadow free spectral-temporal features over larger areas. We developed a processing chain, which automatically downloads the required imagery, creates cloud/cloud-shadow masks [*Zhu and Woodcock,* 2012], transforms DNs to surface reflectance [*Richter,* 2016] and calculates spectral indices for each individual scene. All cloud/cloud-shadow free observations of the pre-processed data are then combined to spatially consistent spectral-temporal features that can be used for wall-to-wall analysis over large focus regions comprising multiple Landsat frames [*Potapov et al.,* 2014].

Throughout the last year the processing chain was further developed and was used to derive a recent and historic coverage of high quality image composites for the project's focus deltas. Thereby temporal coverage focused on those years with relatively good satellite data acquisition frequency. For years where cloud cover and/or acquisition frequency prohibited a complete cloud free coverage of the focus region, the observation period was extended to epochs, i.e. multiple years. Table 1 lists the generated products and the data used for the areas of interest (deltas and surroundings). All Landsat 4-5, Landsat 7, and Landsat 8 scenes with cloud cover of less than 60% have been used in the creation of the image products. Figure 1 and Figure 2 show the full extent of the derived synthetic images with areas of change.

Table 1. Overview over the main Synthetic Landsat Imagery datasets created for the project's focus deltas.

DELTA	EPOCH	Number of WRS-2 Frames	Number of Scenes	Landsat Sensors
ARD	2000-2003	21	631	5, 7
ARD	2012-2015	21	1043	7, 8
GBD	1994	8	60	5
GBD	2014	8	234	7, 8
MRD	1999-2001	11	480	7
MRD	2013-2015	11	888	7,8

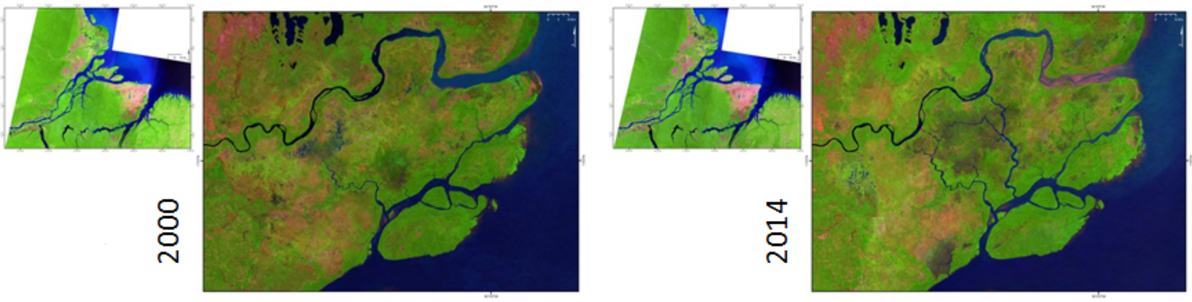

Figure 1. Synthetic images of 2000 and 2014 of the Amazon River Delta.

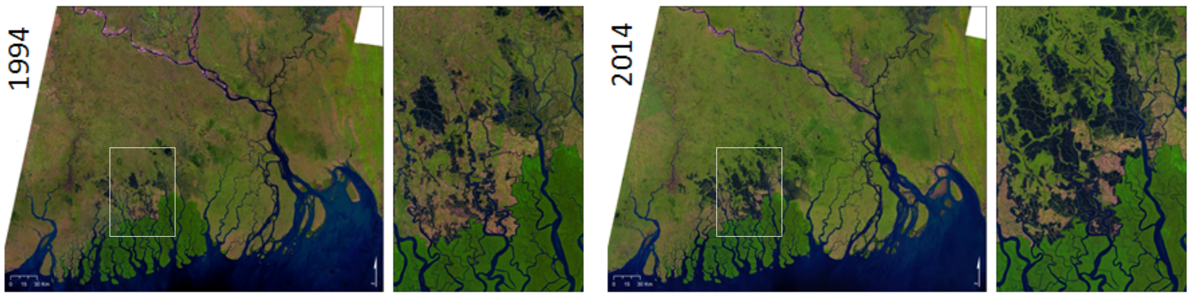

Figure 2. Synthetic images of 1994 and 2014 of the Ganges Brahmaputra River Delta.

2. Land use/land cover change analysis in the GBD

Land use/land cover (LULC) is very important information and is critical for spatial planning, for climate change, habitat and biodiversity studies and as variable in modeling systems (e.g., ecosystem, hydrologic, atmospheric models). Remote sensing data is one of the predominant data sources used to derive spatially explicit LULC information over large areas. However, so far land cover products of the GBD are derived over larger regions with coarse scale resolution data [*Chaudhuri and Mishra,* 2016] or with higher (Landsat-like) resolution for smaller selected regions [*Islam et al.,* 2016]. Instead we performed a higher resolution LCLU classification for two years over the whole delta spanning several Landsat frames. In the last annual progress report the initial 2014 classification has already been presented. The classification has been refined and a second classification was conducted for the year 1994.

Eight LULC classes have been mapped: settlements, agriculture, woodland, mangroves, sandbanks, mudflats, wetlands and water. For these classes more than 1000 reference polygons have been manually digitized for each year by visual interpretation of the Landsat and GoogleEarth images. The reference data and 56 of the spectral-temporal features have been used for the classification with a Random Forest classifier.

Figure 3 shows the LULC classification map of 2014 and a comparison to 1994 for two selected areas, showing i) the dynamic coastal morphology in the eastern part of the delta with accretion and erosion processes; and ii) an increase of aquaculture in the north of the Sundarbans. Table 2 shows that the area of aquaculture almost doubled between 1994 and 2014 while most other LULC classes were relatively stable.

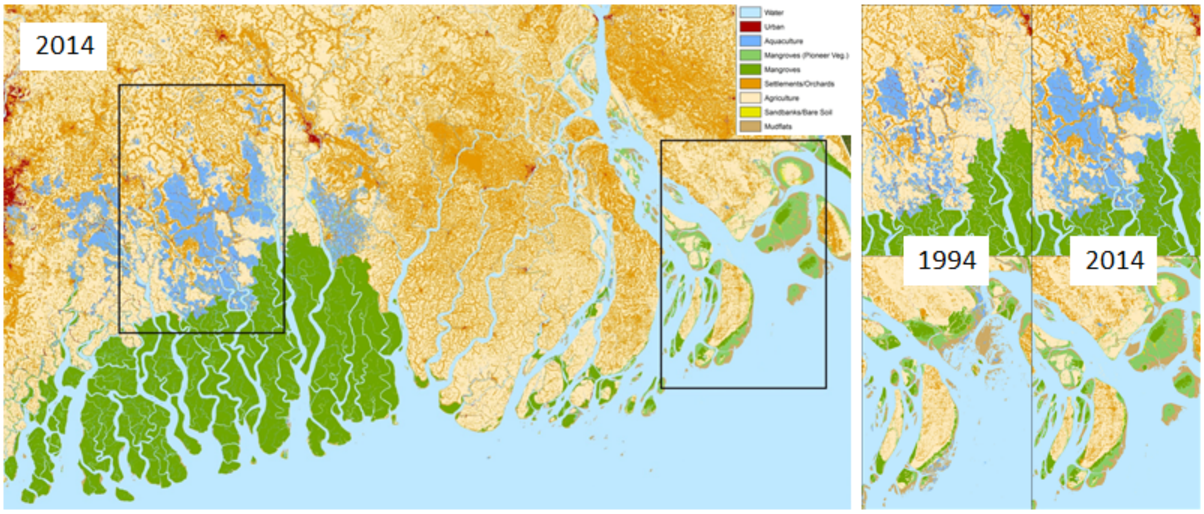

Figure 3. LULC map of the year 2014 (left) and two regions of major change showing increase of wetlands (upper right) and the dynamic costal region (lower right).

Table 2. Change of mapped LULC classes.

	1994		**2014**	
	Km²	%	Km²	%
Water	18,287	28.53	17,965	28.03
Urban	501	0.78	713	1.11
Aquaculture	1,469	2.29	2,636	4.11
Mangroves (Pioneer Veg.)	659	1.03	1,204	1.88
Mangroves	6,377	9.95	6,495	10.08
Settlements/Orchards	9,947	15.52	12,616	19.69
Agriculture	26,094	40.72	21,578	33.67
Sandbanks/Bare	12	0.02	79	0.12
Mudflats	735	1.15	831	1.30

3. Dataset creation for coastline and river course change analysis

Coastline and river course change is an important process in river deltas and its monitoring is essential e.g., for coastal resource management and environmental protection [*Rhaman et al.,* 2011]. A processing chain was developed to semi-automatically derive land/water areas in vector format data based on satellite imagery time series data. The workflow included the following steps: i) calculation of the Automated Water Extraction Index (AWEI) [*Feyista et al.,* 2014] from spectral-temporal features; ii) land/water classification by applying a threshold on the index; iii) vectorization, including smoothing of land/water border and removal of lakes and reservoirs (water areas completely surrounded by land); iv) derivation of erosion and accretion/deposition areas. Examples of the derived datasets are shown in Figure 4 (vector dataset of land/water line, GBD) and Figure 5 (vector dataset of erosion and accretion/deposition areas, ARD). Following this approach, datasets have been created for the ARD (years: 2000 and 2014) and the GBD (years: 1988 and 2010).

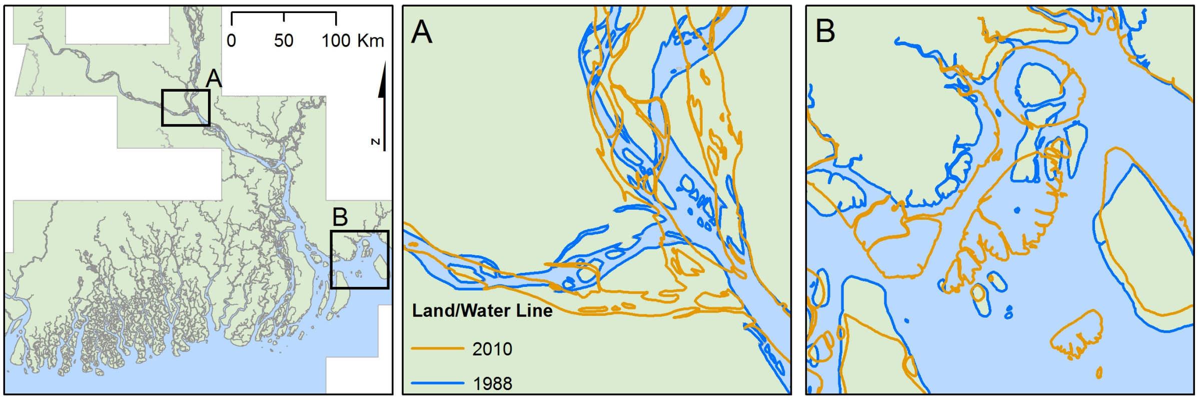

Figure 4. Land/Water Line change in the GBD between 1988 and 2010.

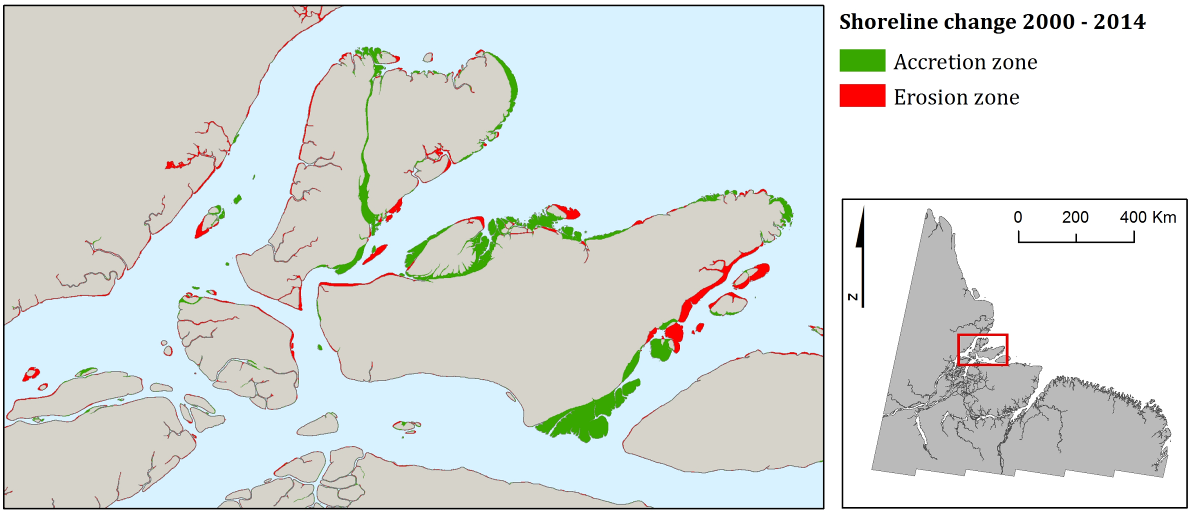

Figure 5. Accretion and erosion/deposition zones in the ARD between 2000 and 2014.

For the MRD a similar dataset has been generated by manual digitization of Landsat imagery for two sub-regions (Mekong River mouth and Rach Gai) over 25 years (1990-2015) (Figure 6). At a cost of high human labor input the dataset has a high accuracy. Future work in the context of coastal morphology will focus on further refinements on the algorithm based on comparison analyses between automated and manual approaches for coastline extraction.

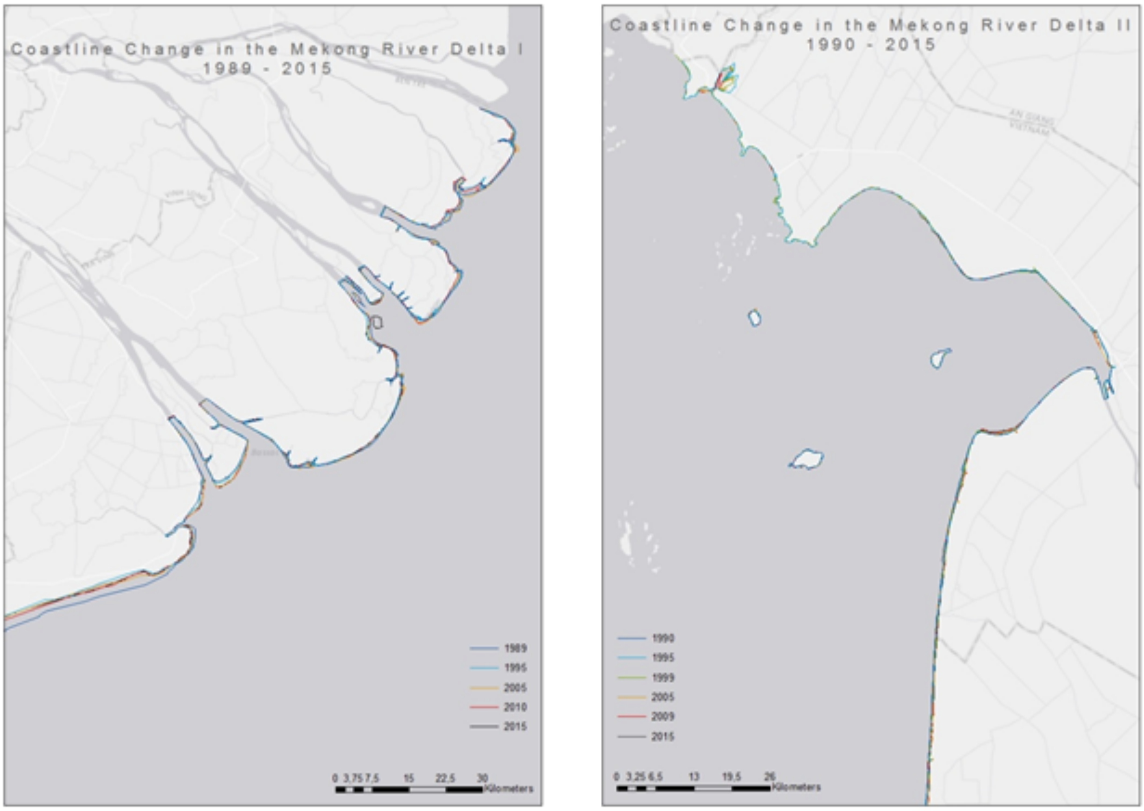

Figure 6. Yearly coastline change over 25 years in the MRD.

4. Land use/land cover classification and long-term crop monitoring in the Mekong river delta with MODIS time series

The Mekong Delta in Vietnam is the national focus region in terms of agricultural production. It provides 50% of Vietnam's food, and 90% of Vietnam's rice exports. These outstanding advantages are threatened by a number of developments, chief of which is the ongoing and planned development of hydropower dams along the main stem of the Mekong, altering the hydrology and sediment balance of the river vital for the high agricultural outputs in the delta. Furthermore, the increased commercialization of existing land resources and the growing requirements for the production and securing of food in the Delta are the principle drivers for land use and land cover changes in the region. The growing demand for food is first and foremost addressed by increased annual agricultural outputs that in many cases are based on the intensification of annual harvest cycles through irrigation. In view of this, the monitoring of land cover and land use as well as the analyses of cultivation schemes and agricultural practices based on Earth Observation data is a highly important task for regional planning purposes.

In the MRD single to triple season rice paddy dominate the agricultural landscape. In order to analyze the cropping cycles in detail very high temporal resolution imagery with daily global coverage is necessary. Furthermore, to analyze gradual trends and shifts in the cultivation scheme long time series of satellite data are required. For this reason, 15-years (2000-2015) of satellite data from the Moderate-Resolution Imaging Spectrometer (MODIS) instrument aboard the Terra and Aqua satellites were used. The standard MOD13Q1/MYD1Q1 Normalized Difference Vegetation Index (NDVI) 16-day composite products from Terra/Aqua were combined in this study resulting in a quasi 8-day times series of gridded level-3 NDVI products at 250-meter spatial resolution. Although the use of temporal composites effectively reduced the amount of clouds and noise, the NDVI time series still showed significant variances, unrelated to phenology or relevant land surface changes. The interpolation of data gaps and the smoothing of high-frequent noise in the trajectory were therefore essential for the further use of the time series. This was carried out by applying a Savitsky-Golay (SG) smoothing filter as implemented in the TIMESAT software developed by [*Jönsson and Eklundh,* 2004]. Finally, phenological metrics, such as growing season amplitude, or the time point of the beginning and ending of the growing season, were extracted for each growing season, based on the interpolated and smoothed time series (see Figure 7).

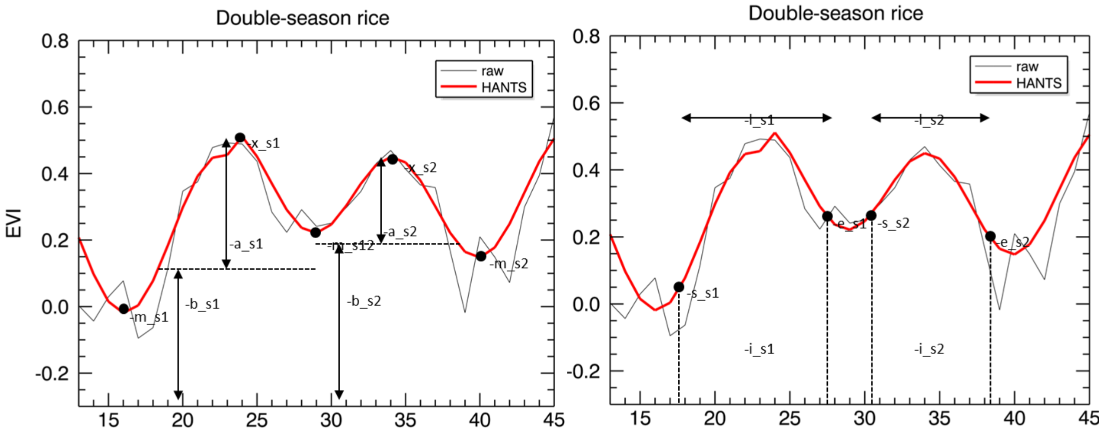

Figure 7. Extraction of phenological parameters based on a NDVI time series for a double season rice paddy pixel

This information was subsequently used to classify different crops and agricultural land uses based on the intra-annual time series information using a supervised classification procedure. Below you can see a comparison between the crop and land use classification for the Mekong Delta, including different number of harvest cycles (left) compared to standard products for the Delta such as the GlobeCover Product (middle) or the MODIS standard land cover product (right).

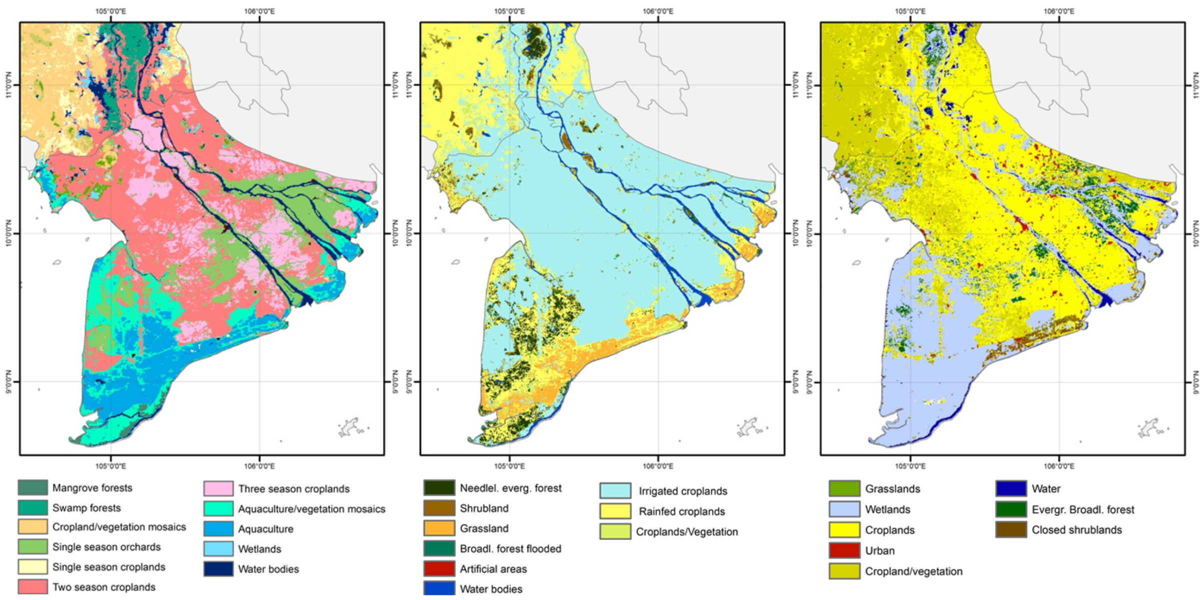

Figure 8. Comparison of our generated LULC map of the MRD with other products available for the region.

Currently long term analyses on the harvest patterns over a period of 15 years are in preparation in order to analyze the impact of the annual flooding regime on agricultural productivity in the region. This is highly important since flood patterns in the Delta will change fundamentally, due to changes in the hydrology as a result of upstream dam and hydropower developments.

Publications:

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5. River deltas animation

The group's research findings on river deltas in general and from the DELTAS project in particular have been condensed in an animation for a wide, including non-scientific, audience. The animation was created at the German Aerospace Center in cooperation with the Department of Science Communication and Visualization. It addresses the importance and challenges of the world's deltas and can be accessed online: http://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-10013/#gallery/25966. The animation is disseminated to project partners and any interested persons to communicate the scientific work conducted in C. Künzer's group.

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Sebesvari, Z., F.G. Renaud, S. Haas, Z.D. Tessler, M. Hagenlocher, J. Kloos, S. Szabo, A. Tejedor and C. Kuenzer (2016). A review of vulnerability indicators for deltaic social–ecological systems. *Sustainability Science (Special Feature)*, 1-16.

Sebesvari, Z., E. Foufoula-Georgiou, I. Harrison, E.S. Brondizio, T. Bucx, J.A. Dearing, D. Ganguly, T. Ghosh, S.L. Goodbred, M. Hagenlocher, R. Hajra, C. Kuenzer, A.V. Mansur, Z. Matthews, R.J. Nicholls, K. Nielsen, I. Overeem, R. Purvaja, Md.M. Rahman, R. Ramesh, F.G. Renaud, R.S. Robin, B. Subba Reddy, G. Singh, S. Szabo, Z.D. Tessler, C. van de Guchte, N. Vogt and C.A. Wilson (2016), Imperatives for sustainable delta futures, *Global Sustainable Development Report (GSDR) 2016 Science Brief.*

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Kuenzer, C., P. Leinenkugel, J. Huth, M. Ottinger, F. Renaud, E. Foufoula-Georgiou, T. Vo Khac, L. Trinh Thi, S. Dech, P. Koch and M. Le Tissier (2015), *The Potential of Time Series Based Earth Observation for the Monitoring of Large River Deltas. AGU Fall Meeting 2015, 14.-18. Dec. 2015, San Francisco, USA*.

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Leinenkugel, P., J. Huth, M. Ottinger, A. Dietz, I. Klein and C. Kuenzer (2016), Water availability and hydrological modelling, *IGSTC Workshop: Recent advancement in online/remote water quality monitoring and management technologies, Chennai, India, 2-4 February 2016.*

Further Publications 2015-2016

Kuenzer, C., F. Moder, V. Jaspersen and S. Dech (2016), A Water related Information System for the Sustainable Development of the Mekong Delta: Experiences of the German-Vietnamese WISDOM Project. In: Integrated Water Resources Management: Concept, Research and Implementation, *Springer,* 11-22.

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United Nations University

Research Themes and Accomplishments during 2015-2016

UNU-EHS leads the activities to develop the Global Delta Vulnerability Index (GDVI) within the project team. In order to advance our understanding of the spatial variability of vulnerability and risk to environmental hazards on the sub-delta level we 1) develop a unified framework for assessing risk and vulnerability that will be adapted locally, 2) define indicators that are quantifiable at the sub-delta scale and transferable in different delta contexts capable to capture the spatial variability of vulnerability, 3) apply a flexible indicator development process that combines scientific and local stakeholder-based approaches, 4) conduct an assessment in the three demonstration deltas at the sub-delta scale, 5) develop an indicator-library to support future assessments and finally 6) draw lessons for application in other delta environments.

1. Review of vulnerability indicators used in the three model deltas

The Delta-SES-Framework (Sebesvari et al. 2016) provided the structure for a review of vulnerability indicators used in past assessments in the three model deltas. Based on the reviewed studies, we noted that comprehensive social-ecological assessments were seldom implemented in the past. Even in assessments explicitly aiming to capture both sub-systems, indicators for social susceptibility and coping/adaptive capacities overwhelmed those for the ecosystems (see Figure 1). Moreover, we report on a lack of multi-hazard approaches accounting for the specific vulnerability profiles of sub-delta areas. The indicators reviewed in this paper are suggested to serve as a preliminary "library" of potential indicators to be used for future vulnerability assessments. We advocate for more comprehensive, truly social-ecological assessments which respond to multi-hazard settings and recognize within-delta differences in vulnerability and risk. Such assessments could make use of the proposed framework and list of indicators as a starting point and amend it with new indicators that would allow capturing the complexity as well as the multi-hazard exposure in a typical delta SES. The results of the review have been published in Sebesvari, Z., Renaud, F.G., Haas, S., Tessler, Z., Hagenlocher, M., Kloos, J., Szabo, S., Tejedor, A., Kuenzer, C. (2016), A review of vulnerability indicators for deltaic social–ecological systems. Sustainability Science, 11, 575-590. doi:10.1007/s11625-016-0366-4.

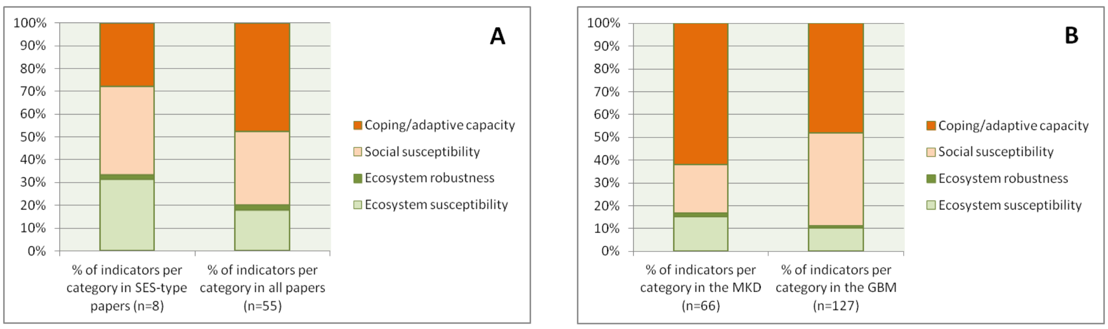

Figure 1A. Comparison of the share of indicators dealing with the four vulnerability domains in SES-type papers vs. all reviewed papers. **Figure 1B.** Comparison of the share of indicators dealing with the four vulnerability domains in the papers related to the Mekong Delta (MKD) and Ganges-Brahmaputra-Meghna Delta (GBM).

2. Development of the GDVI

The Global Delta Vulnerability and Risk Index (GDVI) was developed by the UNU team in the reporting period. It is based on the inclusive SES-centered framework for vulnerability assessments. The GDVI allows for the identification and hazard-driven combination of different sets of vulnerability indicators to be identified which can then be combined for deltas globally in a modular way. The modular structure allows being responsive to the specific multi-hazard settings of a given delta SES while also considering the interactions between the hazards in one given location. It therefore represents a departure from the usual fixed set of indicators used in existing vulnerability and risk assessments.

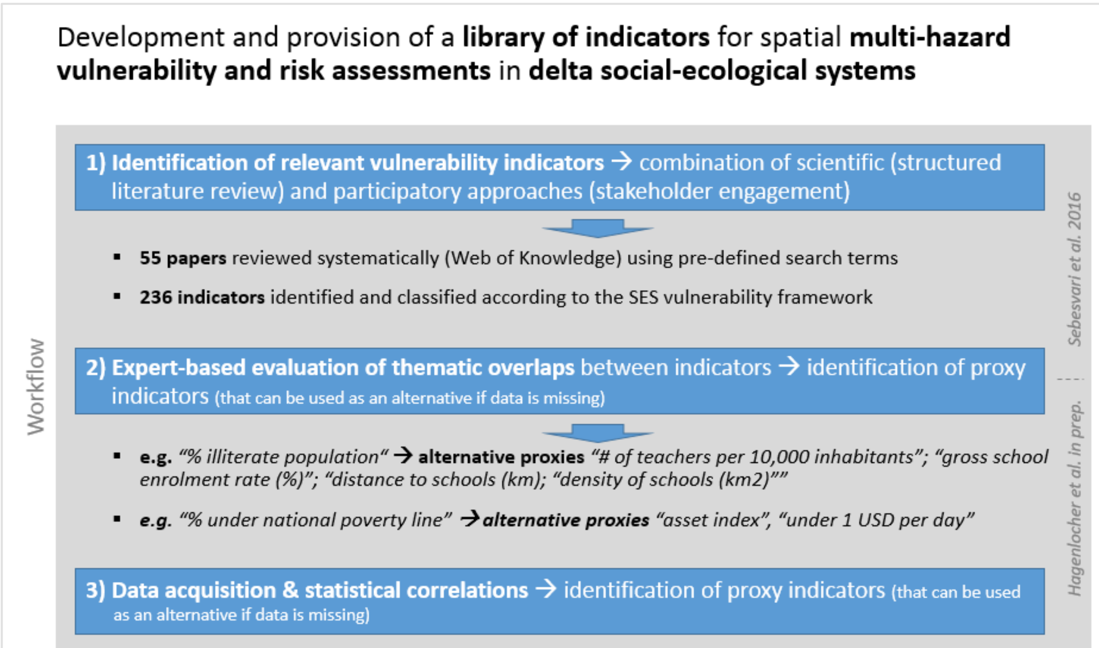

Figure 2. Workflow for the construction and use of the GDVI library.

Major achievements in the reporting period included the development of this modular set of indicators, the demonstration of their use in three model deltas in spatially explicit vulnerability and risk assessments as well as the presentation and discussion of preliminary assessments in one of the deltas (Amazon Delta). The workflow for the construction and use of the GDVI library is shown in Figure 2. The construction of the index is presented in Figure 3.

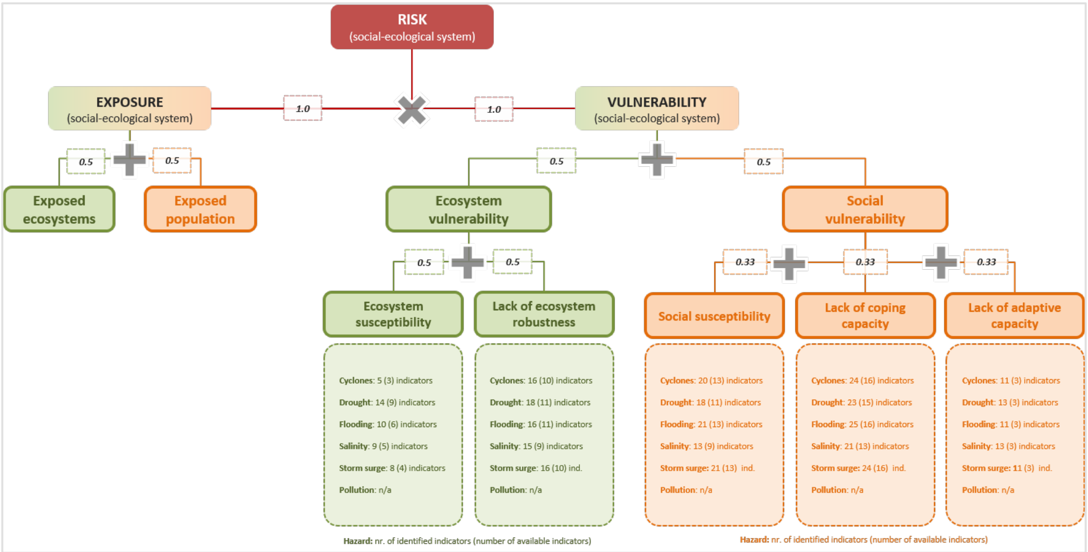

Figure 3. Construction of the GDVI.

3. Stakeholder consultation in the Amazon Delta

The second field mission to the Amazon Delta was co-organized by The Indiana University Bloomington and UNU-EHS in partnership with the Universidade Federal do Pará between 2 and 13 May 2016. The research team consulted various stakeholders in the municipialities Belém, Amapa, Soure, and Gurupá. During facilitated discussions, invited participants discussed the risk and vulnerability maps as well as weighted the indicators used for the assessment. Participants were representatives of sectoral agencies such as planning, disaster risk management, health, agriculture, forestry, as well as scientists, and nongovernmental organizations. The outcome of the consultation process was an improved understanding of the deltas risk and vulnerability landscape, a revised indicator list for the GDVI, and weights allocated to individual indicators based on expert opinion. Figure 4 shows the locations visited while Figure 5 shows how weights given to individual indicators might vary at different locations in the Delta.

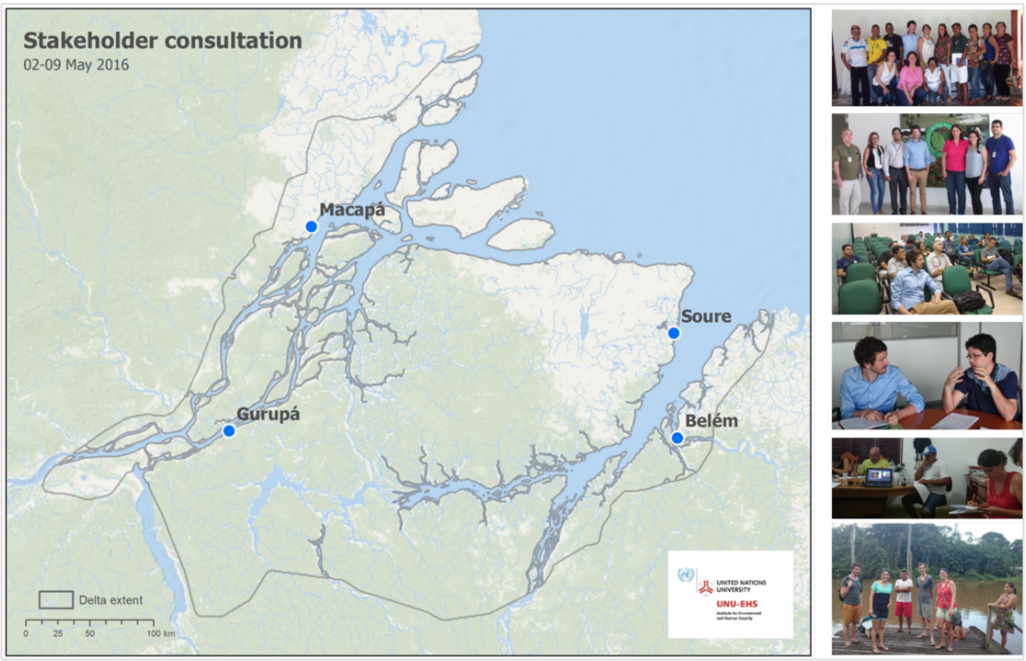

Figure 4. Stakeholder consultation in the Amazon in May 2016

SOCIAL SUSCEPTIBILITY								
INDICATOR NAME & DESCRIPTION	**WEIGHT**	**MEAN**	**STD**	**Soure**	**Macapa**	**Gurupa**	**Belem_SP**	**Belem**
Children under 5 years (%)	0.075	0.79	0.11	0.73	0.94	0.69	0.75	0.87
Elderly population (> 60 years) (%)	0.068	0.72	0.17	0.72	0.88	0.44	0.75	0.81
Female population (%)	0.048	0.51	0.14	0.75	0.44	0.44	0.50	0.42
Travel time to closest city (in minutes)	0.073	0.77	0.13	0.70	0.75	0.75	1.00	0.67
Population with disabilities (%)	0.060	0.64	0.12	0.61	0.81	0.56	0.50	0.71
Illiteracy (%)	0.067	0.71	0.06	0.65	0.79	0.69	0.75	0.69
Poverty rate (%)	0.086	0.91	0.06	0.83	0.88	0.94	1.00	0.88
Dependency ratio	0.063	0.67	0.12	0.72	0.77	0.50	0.75	0.60
Income per capita (US$)	0.078	0.83	0.10	0.80	0.83	1.00	0.75	0.75
Contribution of agriculture/forestry/fisheries	0.082	0.87	0.12	0.89	0.67	0.88	1.00	0.90
No access to improved sanitation (%)	0.080	0.85	0.10	0.90	0.98	0.75	0.75	0.85
No access to clean water (%)	0.088	0.93	0.05	0.93	0.96	0.88	1.00	0.90
No access to electricity (%)	0.080	0.85	0.14	0.78	0.90	0.94	1.00	0.65
Homicide	0.054	0.57	0.25	0.42	0.60	0.44	1.00	0.40
	1.00	10.62						
LACK OF COPING CAPACITY								
INDICATOR NAME & DESCRIPTION	**WEIGHT**	**MEAN**	**STD**	**Soure**	**Macapa**	**Gurupa**	**Belem_SP**	**Belem**
No access to media (radio/TV) (%)	0.074	0.75	0.12	0.88	0.75	0.56	0.75	0.81
Early warning systems	0.061	0.61	0.14	0.75	0.71	0.44	0.50	0.67
Access to shelter	0.064	0.64	0.11	0.65	0.77	0.56	0.50	0.73
No access to waste water treatment (%)	0.081	0.82	0.05	0.80	0.85	0.88	0.75	0.83
Access to local markets	0.060	0.60	0.11	0.78	0.54	0.63	0.50	0.56
Access to transportation network	0.074	0.75	0.14	0.88	0.75	0.81	0.50	0.79
No motorbike/motorcyle (%)	0.056	0.56	0.11	0.75	0.52	0.56	0.50	0.46
Availability of emergency services (hospitals, police, fire brigade)	0.079	0.79	0.18	0.90	0.88	0.75	0.50	0.94
Availability of national food reserves (yes/no)	0.082	0.82	0.08	0.92	0.79	0.75	0.75	0.90
Hospital beds per 1,000 inhabitants	0.069	0.69	0.11	0.70	0.79	0.69	0.50	0.77
Public health expenditure (%)	0.072	0.72	0.15	0.70	0.69	0.81	0.50	0.90
Private health expenditure (%)	0.060	0.60	0.11	0.67	0.48	0.75	0.50	0.60
Gross savings (%)	0.053	0.53	0.11	0.60	0.40	0.69	0.50	0.48
Access to credit/bank loan (%)	0.063	0.63	0.15	0.78	0.52	0.69	0.75	0.44
Micro-Insurance coverage (%)	0.053	0.53	0.12	0.70	0.40	0.63	0.50	0.44
	1.00	10.06						
LACK OF ADAPTIVE CAPACITY								
INDICATOR NAME & DESCRIPTION		**MEAN**	**STD**	**Soure**	**Macapa**	**Gurupa**	**Belem_SP**	**Belem**
Foreign direct investment (% of GDP)	0.273	0.56	0.12	0.60	0.52	0.44	0.75	0.50
Existing / previous adaptation projects	0.369	0.76	0.04	0.78	0.80	0.69	0.75	0.79
Expenditure on innovation & research (in % of GDP)	0.358	0.74	0.17	0.68	0.95	0.75	0.50	0.81
	1.00	2.06						

Figure 5. Indicator weights as seen by stakeholders in the Amazon Delta in May 2016 – preliminary results as of May 2016

Future Work (2016–2017)

Research activities:

1. The publication of the methodology, the library-approach, the final set of indicators, as well as GDVI results for at least 3 deltas is priority for the upcoming work period. The products (vulnerability and risk maps) will be made available online for the public while the geospatial data from both global data repositories and national data providers will be made available to the extent possible accounting for data rights.

2. The team at UNU-EHS will build on the work done in the frame of the BF-DELTAS project and will apply the GDVI in other deltas including the Mississippi Delta, will compare it with other risk and vulnerability assessment methodologies (e.g. the SoVi) and will further push the boundaries by focusing for example on urban-rural differences.

Activities:

1. The UNU team will contribute regularly to the DELTAS cyber-seminars;
2. Fabrice Renaud will continue his work as a guest-editor of a special issue "Sustainable Deltas: Livelihoods, Ecosystem Services and Policy Implications" in the journal "Elementa"
3. Fabrice Renaud and Zita Sebesvari will represent the UNU team at the ESPA Deltas Final UK event, 22-23rd Nov 2016 on Sustainable Development Goals in Deltas. Zita Sebesvari

will deliver a presentation on "Imperatives for sustainable delta futures" (based on the respective UN science brief)
4. Fabrice Renaud will represent the UNU team at the AGU Fall Meeting in San Francisco in December 2016 as well as at the end-of-the-project meeting, as requested by BF, at the 2016 AGU Fall meeting on Dec 10-11, 2016.
5. The UNU team (Fabrice Renaud, Michael Hagenlocher and Zita Sebesvari) will participate in the DELTAS stakeholders and research meeting at the partner institution CUNY, in Sept 12-16, 2016.

Publications

Sebesvari, Z., Renaud, F.G., Haas, S., Tessler, Z., **Hagenlocher, M.,** Kloos, J., Szabo, S., Tejedor, A., Kuenzer, C. (2016), A review of vulnerability indicators for deltaic social–ecological systems. *Sustainability Science*, 11, 575-590. doi:10.1007/s11625-016-0366-4

Renaud, F.G., Szabo, S., Matthews, Z., (2016) Sustainable deltas: livelihoods, ecosystem services, and policy implications. *Sustainability Science, 11,* 519–523. doi:10.1007/s11625-016-0380-6

Brondizio, E., E. Foufoula-Georgiou, S. Szabo, N. Vogt, **Z. Sebesvari, F. G. Renaud**, A. Newton, E. Anthony, A. V. Mansur, Z. Matthews, S. Hetrick, S. M. Costa, Z. Tessler, A. Tejedor, A. Longjas, and J. A. Dearing (2016), "Catalyzing action towards the sustainability of deltas", *Current Opinion in Environmental Sustainability*, *19*, 182-194, doi: doi:10.1016/j.cosust.2016.05.001.

Sebesvari, Z., E. Foufoula-Georgiou, I. Harrison, E.S. Brondizio, T. Bucx, J.A. Dearing, D. Ganguly, T. Ghosh, S.L. Goodbred, **M. Hagenlocher**, R. Hajra, C. Kuenzer, A.V. Mansur, Z. Matthews, R.J. Nicholls, K. Nielsen, I. Overeem, R. Purvaja, Md.M. Rahman, R. Ramesh, **F.G. Renaud**, R.S. Robin, B. Subba Reddy, G. Singh, S. Szabo, Z.D. Tessler, C. van de Guchte, N. Vogt, and C.A. Wilson (2016), "Imperatives for sustainable delta futures", *Global Sustainable Development Report (GSDR) 2016 Science Brief.*

Szabo, S., E. Brondizio, **F.G. Renaud**, S. Hetrick, R. J. Nicholls, Z. Matthews, Z. Tessler, A. Tejedor, **Z. Sebesvari**, E. Foufoula-Georgiou, S. da Costa, and J. A. Dearing (2016), "Population dynamics, delta vulnerability and environmental change: comparison of the Mekong, Ganges-Brahmaputra and Amazon delta regions", *Sustainability Science*, doi: 10.1007/s11625-016-0372-6.

Szabo, S., R.J. Nicholls, B. Neumann, **F.G. Renaud**, Z. Matthews, **Z. Sebesvari**, A. Agha Kouchak, R. Bales, C.W. Ruktanonchai, J. Kloos, E. Foufoula-Georgiou, P. Wester, M. New, J. Rhyner, and C. Hutton (2016), Making SDGs work for climate change hotspots, *Environment: Science and Policy for Sustainable Development*, accepted.

Szabo, S., **F. Renaud**, S. Hossain, **Z. Sebesvári**, Z. Matthews, E. Foufoula-Georgiou, and R.J. Nicholls (2015), "New opportunities for tropical delta regions offered by the proposed Sustainable Development Goals", *Environment: Science and Policy for Sustainable Development*, *57*(4), doi:10.1080/00139157.2015.1048142.

Presentations

List of contributions to conferences:
Fabrice Renaud co-organized a session "River deltas at the crossroads: transformative change for people and ecosystems" at the IUCN World Conservation Congress, Hawai, 02.09.2016

Zita Sebesvari presented the GDVI approach and results at the Japan Geoscience Union Meeting, Makuhari Messe International Conference Hall 2-1 Nakase, Mihama-ku, Chiba-city, 261-0023, Japan. 26.05.2016: "The GDVI – A blueprint for spatial vulnerability assessments in deltas facing multiple hazards"

Fabrice Renaud co-convened the session "DELTAS: multidisciplinary analyses of complex systems" organized at the Japan Geoscience Union Meeting, Makuhari Messe International Conference Hall 2-1 Nakase, Mihama-ku, Chiba-city, 261-0023, Japan. 26.05.2016

The team actively contributed to the UNISDR Science and Technology Conference on the Implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030, 27.01. 2016, Geneva. Zita Sebesvari presented a poster entitled "Using Participatory Approaches to Identify Vulnerability Indicators for Social-Ecological Systems Facing Multiple Hazards" at the conference, Fabrice Renaud co-organized the conference; Fabrice Renaud, Michael Hagenlocher and Zita Sebesvari served as a rapporteur in several sessions

Fabrice Renaud co-convened a scientific session "Sustainable Deltas: Multidisciplinary Analyses of Complex Systems" at the AGU Fall Meeting 17.12.2015 with CSDMS/INSTAAR, University of Texas at Austin, University of Southampton. The double-session hosts 16 oral presentations and 20 poster contributions.

Zita Sebesvari delivered an oral presentation at the AGU Fall Meeting 17.12.2015: "Development of Vulnerability Indicators for Deltaic Social-Ecological Systems Facing Multiple Environmental and Anthropogenic Hazards".

Special issues:
Fabrice Renaud served as a guest-editor of a special issue "Sustainable Deltas: Livelihoods, Ecosystem Services and Policy Implications" in the Springer journal "*Sustainability Science*" with contribution of several BF-DELTAS researchers. The special issue was published in 2016.

Fabrice Renaud currently serves as a guest-editor of a special issue in "*Elementa*" on 'Sustainable Deltas'.

University of Southampton

Robert Nicholls, Zoe Matthews, John Dearing, Attila Lazar, Angela Baschieri, Sylvia Szabo, Kristine Nilsen

Research Themes and Accomplishments during 2015-2016

This progress update is divided into seven short sections reporting on activities undertaken in year 3 (August 2015-August 2016) and activities to be completed in year 4. These include updates on: data availability, a special issue in Sustainability Science, collaboration with WCMC, collaboration with Kings College, a research visit from Rituparna Hajra (Jadavpur University, India) work on the SDGs in climate hotpots and conference presentations. Included in the report is also a list of recent publications.

The Belmont Deltas Project was scheduled to be completed in year 3. The University of Southampton was granted a one-year non-cost extension to finish planned and ongoing activities by the National Environment Research Council (NERC) in April 2016. This will bring the end date for the project at Southampton to December 2017. We anticipate that activities will be completed before the end date.

There has been one change in staff. Dr Sylvia Szabo left her post as a Research Fellow to work for Save the Children in the autumn, 2015. However, Sylvia continues to collaborate on papers associated with the Belmont project. Kristine Nilsen was recruited in February 2016 as Sylvia's replacement. Because of the time-lapse between Sylvia leaving and the recruitment of Kristine, Kristine's contract will end in May 2017.

1. Availability of data

The University of Southampton has obtained the following datasets:

Ganges–Brahmaputra- Meghna Delta:

- The Household Income and Expenditure Survey (HIES 1991; 1995-96; 2005; 2010)
- The Demographic Health Survey with GIS located enumeration areas (2007; 2011)
- The Bangladesh Population and Housing Census (sampling fraction: 10%, 1991; 2001; 2011)
- The ESPA Longitudinal Survey on Health, Livelihoods and Ecosystem Services in Populous Deltas (2014-2015)

The National Bureau of Statistics is scheduled to release the HIES 2015 later this year. Once this survey round will become available, University of Southampton will purchase to provide up to date estimates on planned analysis.

Mekong delta:

- The Household Living Standards Survey (HLSS 1992; 2002; 2012)
- The Land Census 2000
- The Mekong River Commission data
- The Vietnam Population and Housing Census (sampling fraction 15%; 2009)
- The Population and Housing Census of Cambodia (2008)
- The Cambodia Socioeconomic Survey (2009; 2013)

Brazil:

- The Brazil Consumer Expenditure Surveys (2002-03; 2008-09).

Following a large number of articles published in the first two years of the Belmont Deltas Project, a full metadata review of available surveys were conducted to identify gaps and opportunities for future analysis. Following the review, it was decided to focus on the Mekong and Bangladesh datasets in year 3. This decision was reached because subnational data boundaries identifying the Amazon delta in the Brazil Consumer Expenditure surveys can only be obtained by processing the data in at the National Statistics Office in Brazil due to disclosure risks. A subsequent assessment made of the sample design of the surveys showed a limited sample coverage of the Amazon delta. The sample also predominantly consisted of urban households. Both of these issues could likely lead to biased results when analysing the socioeconomic surveys and it was therefore decided not to pursue any analysis further.

In addition, the University of Southampton is working closely with partner organisation to combine information from these sample surveys with datasets containing information on environmental variables.

2. Sustainability Science: Special Issue

In collaboration with Fabrice Renaud (United Nations University), Sylvia Szabo and Zoe Matthews (University of Southampton) edited and published a special issue on 'Sustainable deltas: livelihoods, ecosystem services and policy implications' in the journal *Sustainability Science* 2016 (11)4. The special issue consisted of an editorial article and 12 substantive articles with 7 of them originating from partners associated with the Belmont Deltas Project.

The special issue 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. The special issue can be viewed in its entirety by accessing:
http://link.springer.com/journal/11625/11/4?wt_mc=alerts.TOCjournals

Articles in the special issue associated with University of Southampton:

Renaud, F.G., **Szabo, S.** and **Matthews, Z.** (2016). Sustainable deltas: livelihoods, ecosystem services, and policy implications. *Sustainability Science* 11(4). doi:10.1007/s11625-016-0380-6

Szabo, S., Brondizio, E., Renaud, F.G., Hetrick, **R.J., Nicholls**, R.J., **Matthews, Z.**, Tessler, Z., Tejedor, A., Sebesvari, Z., Foufoula-Georgiou, E., da Costa., S and **Dearing, J.** (2016) Population dynamics, delta vulnerability and environmental change: comparison of the Mekong, Ganges–Brahmaputra and Amazon delta regions. *Sustainability Science* 11(4). doi:10.1007/s11625-016-0372-6

de Araujo Barbosa, C.C., **Dearing, J.**, **Szabo, S.** Hossain, S., Binh Nguyen Thanh, Nhan Dang Kieu and **Matthews, Z.**, (2016) Evolutionary social and biogeophysical changes in the Amazon, Ganges–Brahmaputra–Meghna and Mekong deltas *Sustainability Science* 11(4). doi:10.1007/s11625-016-0371-7

Sebesvari, Z., Renaud, F.G., Haas, S. Tessler, Z., Hagenlocher, M., Kloos, J., **Szabo,S.**, Tejedor,A., and Kuenzer, C., (2016) A review of vulnerability indicators for deltaic social–ecological systems. *Sustainability Science* 11(4). doi:10.1007/s11625-016-0366-4

3. Interdisciplinary collaborations

The University of Southampton has undertaken several formal interdisciplinary collaborations in the last year.

3.1 Research visit

In May/June 2015, the University of Southampton hosted Ms Rituparna Hajra, Research Fellow at the University of Jadavpur. Ms Hajra's work focusses on the socioeconomic effects of environmental factors in the Sundarbans area of India. The collaboration resulted in one published paper and one accepted paper to appear:

Szabo, S., Hajra, R., Baschieri, A., and **Matthews, Z**. (2016) Inequalities in human well-being in the urban Ganges Brahmaputra Meghna Delta, *Sustainability* 8(7), DOI: 10.3390/su8070608

Hajra, R., Ghosh, T., **Szabo, S**., Tessler, Z., **Matthews, Z**. and Foufoula-Georgiou, E (2016), Natural hazards, livelihoods and sustainable development: Evidence from the Indian Sundarban Delta, *Sustainability Science* (to appear)

3.2 UNEP- WCMC

After contact with UNEP-WCMC was initiated in year 2, a new comprehensive terms of reference (ToR) with UNEP-WCMC was developed and signed in October 2015 formalising the collaboration. The ToR includes activities that will result in to two papers on the impacts of environmental change on food security and health outcomes in the Ganges-Brahmaputra and Mekong deltas. Linking environmental data to household survey data is challenging due to the availability of data, incompatible datasets and measurement error. As a proxy for environmental impact, we use normalised difference vegetation index (NDVI) obtained by satellite remote sensing and combine it with GIS-located information on health and socioeconomic characteristics obtained from sample surveys. NDVI informs us about the combined effect of rainfall, temperature and land cover allowing for assessment of localised crop growing conditions on nutrition and health outcomes. NDVI data are easily accessible high-resolution time series data covering many low-income countries. Controlling for household and individual characteristics, multilevel random regression models have been fitted to assess the link between spatial variation in growing conditions and the resilience of households to cope with food availability.

The first paper assesses the suitability of using NDVI as a proxy for environmental factors and models the impact of NDVI on four different nutrition and health outcomes in the Ganges-Brahmaputra delta in 2007 and 2011. Overall findings suggest a relationship between NDVI and womens' and children nutritional status in specific contexts.

Preliminary results of this work were presented at the AGU conference in Japan 22-26 May, 2016 in the JpGU &AGU joint session on deltas.

An expression of interest submitted to a Special Issue on Deltas in the journal Elementa has been accepted and the full article will be submitted for consideration on 15 October 2016.

Van Soesbergen, A., **Nilsen, K**., Burgess, N., **Szabo, S**., and **Matthews, Z**., "Food and nutrition security trends and challenges in the Ganges-Brahmaputra delta"

The second paper is in the early stages of implementation. Focusing on Cambodia using data sample survey and census data from 2000-2014, the paper will compare delta and non-delta areas to assess vulnerabilities and impacts of environmental factors on food security, nutrition and livelihoods. Using small area estimation techniques, we will quantify spatial differentials and household resilience to localised environmental change and degradation visualised through high-resolution maps. Because of the novel nature of this work, we aim to publish the results in high impact journal.

Nilsen, K., van Soesbergen, A and **Matthews, Z**. (and potentially others). Where You Live Matters: Localising Environmental Impacts on Health Nutrition and Poverty in Cambodia using Small Area Estimation Techniques.

Abstracts of both papers have been submitted to the AGU Fall meeting in San Francisco 12-16 December, 2016.

3.3 University of Exeter and King's College London
A collaboration between W. Neil Adger, University of Exeter and Helen Adams, King's College, London has been initiated to analyse a longitudinal household survey conducted across 3 seasons in Khulna and Barisal Divisions in Ganges-Meghna-Bhramaputra delta conducted by the ESPA project. The collaboration is in the planning stages and aims to analyse linkages between poverty and livelihoods by ecological zones.

4. Consultancies

Analysis of commodity prices
In collaboration with Robert Nicholls, Prof Richard Tol (contracted by the University of Southampton) undertook an analysis of commodity prices (trends and projections) at the national level. This research output can be provided upon request.

5. Environmental hotspots and the SDGs

Led by Sylvia Szabo we worked to develop further some SDG-related issues after the successful publication of a detailed consideration of indicators being used for delta areas in Szabo, S., Renaud, F., Hossain, S., Sebesvári, Z., Matthews, Z., Foufoula-Georgiou, E. and Nicholls, R.J. (2015) New opportunities for tropical delta regions offered by the proposed Sustainable Development Goals. Environment: Science and Policy for Sustainable Development, 57 (4) (doi:10.1080/00139157.2015.1048142). Considering deltas as just one type of vulnerable area among a range of other 'hotspots' – such as drought zones, alpine regions etc, we sought to write a paper which develops the possible indicators for cross boundary areas with similar environmental challenges. The paper is now published:

Szabo, S., Nicholls' R.J., Neumann B., Renaud' F., **Matthews, Z**, Sebesvari' Z, AghaKouchak' A., Bales' R., Warren Ruktanonchai' C, Kloos C., Foufoula-Georgiou' E., Wester, P., New, M., Rhyner' J, Hutton, C , (2016) Making SDGs work for climate change hotspots, Environment: Science and Policy for Sustainable Development, (To appear)

6. Conference sessions and presentations

Special session on climate change and maternal health at the Women Deliver Conference
In May 2016, we organised a special session at the 4th Global Women Deliver conference in Copenhagen, 16-19 May 2016. Women deliver forum gathers academics, activists and high-level policy makers covering all aspects affecting the rights and health of women and girls. The University of Southampton organised a concurrent session on reproductive health and climate change focusing on global and local impacts of environmental degradation and climate change on women's health outcomes in hotspot areas including deltas. The session consisted of presentations from especially invited speakers including Dr Anthony Costello Assistant Director General at the World Health Organisation and member of the Lancet Commission on Health and Climate Change, Dr Ima Kashim, Executive Director of Public

Health and Community Development Center, Nigeria and Evelyn Anyiko young activist (Center for Alterative Development, Uganda). A report on how to mitigate the impacts of climate change in environmental hotspots on women health outcomes and access to health services was submitted to the Women Deliver Secretariat, which will be published later this year through conference proceedings.

AGU Conference May 2016, Japan
Preliminary findings on the below paper was presented in a special session on deltas:
Van Soesbergen, A., Nilsen, K., Matthews, Z., Burgess, N., Food and nutrition security, trends and determinants and challenges in tropical mega deltas.

Oxford Symposium on Population, Migration and the Environment, 21 March 2016
The following paper was presented at the symposium:
Szabo S., et al: Home is where the money goes: determinants and impacts of remittance flows in the Ganges Brahmaputra and Mekong delta regions.

Publications

Szabo, S., Brondizio, E., Hetrick, S., Matthews, Z., Nicholls, R. Renaud, F., Sebesvari, Z., da Costa, S. Dearing, J., Foufoula-Georgiou, E. (2016), Population dynamics in the context of environmental vulnerability: Comparison of the Mekong, Ganges Brahmaputra and Amazon delta regions, Sustainability Science, May 2016, DOI 10.13140/RG 2.1.1072.2320

De Araujo Barbosa, C.C., Dearing, J.A, Szabo S., Hossain, M.S., Nhan, D.K., Binh, N.T., Matthews, Z. (2016), Evolutionary social and bio geophysical changes in the Amazon, Ganges-Brahmaputra and Mekong deltas, Sustainability Science, May 2016, DOI 10.1007/s11625-016-0371-7

Sebesvari, Z., Renaud, F. G., Haas, S. Tessler, Z., Kloos, J., Szabo, S., Tejedor, A., Kuenzer, C. "Vulnerability indicators for deltaic social-ecological systems: a review"

Szabo, S., Hossain, S., Adger, W.N., Matthews. Z. Ahmed, S., Lazar, A.N. and Ahmad, S. (2016) Soil salinity, household wealth and food insecurity in tropical deltas: evidence from south-west coast of Bangladesh, Sustainability Science (11)3, DOI: 10.1007/s11625-015-0337-1

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Brondizio, ES, Foufoula-Georgiou, E, Szabo, S, Vogt, N, Sebesvari, Z, Renaud, FG, Newton, A, Anthony, E, Mansur, AV, Matthews, Z, Hetrick, S, Costa, SM, Tessler, Z, Tejedor, A, Longjas, A, Dearing, JA, (2016) Catalyzing action towards the sustainability of deltas. Current Opinion in Environmental Sustainability 19: 182–94. DOI:10.1016/j.cosust.2016.05.001

Szabo, S, Nicholls, R.J., Neumann B., Renaud, F., Matthews, Z, Sebesvari, Z, AghaKouchak, A., Bales, R., Warren Ruktanonchai, C, Kloos C., Foufoula-Georgiou, E., Wester, P., New, M., Rhyner, J, Hutton, C , (2016) Making SDGs work for climate change hotspots, Environment: Science and Policy for Sustainable Development

Renaud, F., Szabo, S. and Matthews, Z**.** (2016) Sustainable deltas: livelihoods, ecosystem services, and policy implications- Special Feature Editorial, Sustainability Science (2016) 11:519–523 DOI 10.1007/s11625-016-0380-6

Szabo, S., Begum, D. Ahmad, S., Matthews, Z., Streatfield, P. K. (2015) "Population Projections for Ganges Brahmaputra Delta (2011-2051)"CPC Working Paper 63, University of Southampton, available: http://www.cpc.ac.uk/publications/cpc_working_papers.php

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To appear/ under review

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Hajra, R., Ghosh, T., Szabo, S., Tessler, Z., Matthews, Z. and Foufoula-Georgiou, E (2016), Natural hazards, livelihoods and sustainable development: Evidence from the Indian Sundarban Delta, *Sustainability Science* (to appear)

Szabo, S., Adger, N., Matthews, Z. "Home is where the money goes: determinants and impacts of remittances in the Ganges Brahmaputra and Mekong delta regions"

Work in progress

Szabo, S. Wisniowski, A., Nilsen, K. Matthews, Z. "Remittances, food insecurity and gender in Bangladesh"

Nilsen, K., van Soesbergen, A and Matthews, Z. (and potentially others). Where You Live Matters: Localising Environmental Impacts on Health Nutrition and Poverty in Cambodia using Small Area Estimation Techniques.

Van Soesbergen, A., Nilsen, K., Burgess, N., Szabo, S., and Matthews, Z., "Food and nutrition security trends and challenges in the Ganges-Brahmaputra delta"

Szabo, S. Padmadas, S., Falkingham, J. "Is rapid urbanisation exacerbating intra-urban inequalities in child health? Evidence from the least developed countries"

Szabo, S. Padmadas, S., Falkingham, J. "Urbanisation and access to improved water sources: Evidence from the least developed countries"

Ramesh Ramachandran

National Centre for Sustainable Coastal Management
Ministry of Environment, Forest & Climate Change, Koodal Building
Anna University Campus, Chennai, India

Research Themes and Accomplishments during 2015-2016

1. Urban sprawl in the Ganges Delta

Kolkata Metropolitan Area (KMA) is an urban agglomeration of the city of Kolkata, West Bengal, India and is the most urbanized area in the Ganges delta region. KMA consists of 3 Municipal corporations (Kolkata Municipal Corporation (KMC), Howrah Municipal Corporation and Chandannagore Municipal Corporation, also it consists of 38 Municipalities, 72 cities and 527towns and villages. According to the 2011 census data, the total population of KMA is 1,41,12,536. The total area is 1851.41 km^2, making the population density 12,883 per km^2. After independence of India, that River Hugli acted as a barrier to refugee influx in the metropolitan area. Hence, refugee concentration is higher on the eastern bank of the river Hugli within KMA, due to non-existence of any natural barrier between their place of origin (Bangladesh) and destination (eastern part of KMA). Kolkata Municipal Corporation or KMC is responsible for the civic infrastructure and administration of the city of Kolkata.

The civic administrative body administers an area of 200.71 km^2. The city is divided into 144 administrative wards that are grouped into 15 boroughs. The northern part of the city is relatively older than the southern part where population grown significantly after 1947. At present in the eastern part of this metropolitan area is experiencing a more rapid rate of urbanization than the rest of the city. According to the study of WWF-India, the municipal wards in Kolkata could be at risk if the Ganga swells up. A weak drainage system of Kolkata makes it more vulnerable. The methodology given by Birkmann, and Welle (2015) were followed to estimate the vulnerability index of Kolkata city (a urban sprawl inside the stable part of the Ganges Delta) and the initial results were represented in figure 1. Interpretation and validation of vulnerability for the Kolkata municipal area were initiated using various primary and secondary data. The initial results indicated that the susceptibility, coping capacity and adaptive capacity of the urban area come under low to moderate range. The overall vulnerability of the city area was significantly higher than few other mega cities in the world (London, New York etc.). The initial results of the vulnerability studies revealed that Kolkata is in a damage control/ Resistance phase with a scope for further development in adapting to various environmental and social stresses. The major hazard risks in this highly populated area are identified as monsoonal Flood, Cyclone, Earthquake, Heat wave, Pollution (Air, Water, Solid waste) etc.

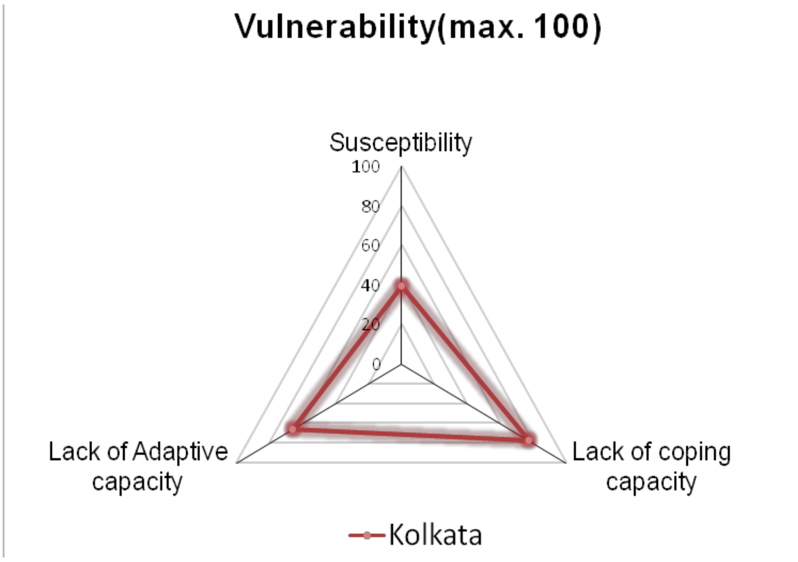


Figure 1. Vulnerability index of Kolkata city (urban sprawl inside the stable part of the Ganges Delta)

Initial result to assess the present condition of Kolkata megacity, situated at the stable part of the Ganges Delta, and indicated that the city at present is positioned in between mal-adaptation and public, supported by the Government. The results are given in the Figure 2.

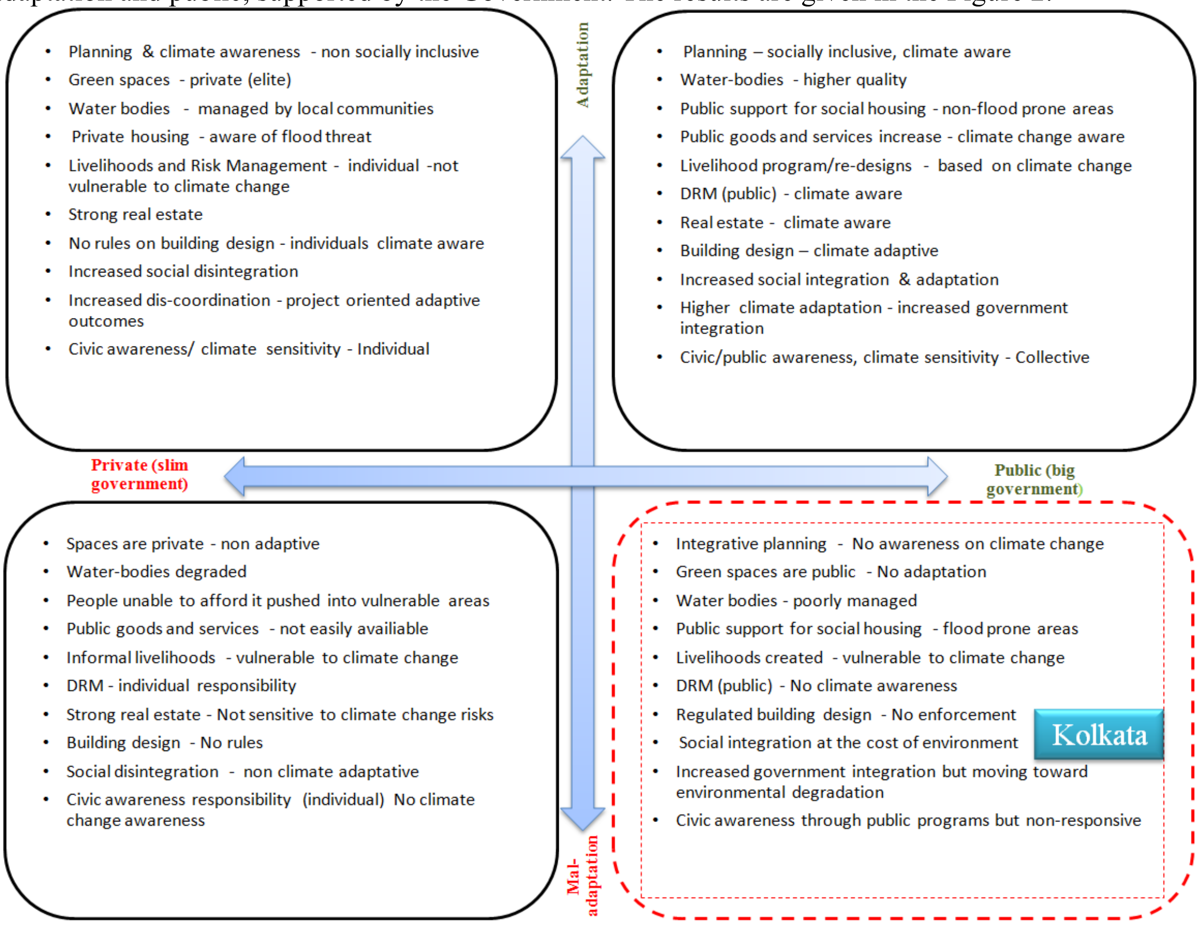


Figure 2. Present scenario of Kolkata megacity derived from the initial interactions with the local stakeholders

2. Climate models: Extreme weather conditions over the GB delta

Tropical cyclone is one of the most devastating weather phenomena in the coastal regions of the world. The destruction is mainly due to strong wind, heavy rainfall and associated storm surge. India has eight maritime states along the eastern and western coast of India is deeply suffering from the storms. Therefore, advanced forecasting techniques with improved warning systems are expected to lead to a significant reduction in the loss of life and damage to the property due to the storms. The present study is focused on the GB delta of Northern Bay of Bengal region which is highly affected by the extreme weather conditions such as tropical cyclones. There are about 9 historical tropical cyclones passed over the GB delta for the period of the last 20 years (Fig.314). In this study, the prediction of a severe cyclonic storm Aila considered as a case study to understand the response of the delta for the extreme weather conditions. It was formed over the Bay of Bengal on May 2009 is investigated using the Weather Research and Forecasting (WRF) model. The severe cyclonic storm Aila crossed the West Bengal coast near Sagar Island between 08:00 and 09:00 UTC on 25th May 2009. It caused a storm surge of 2-3m above tide levels along the West Bengal and Bangladesh coasts, with severe devastation.

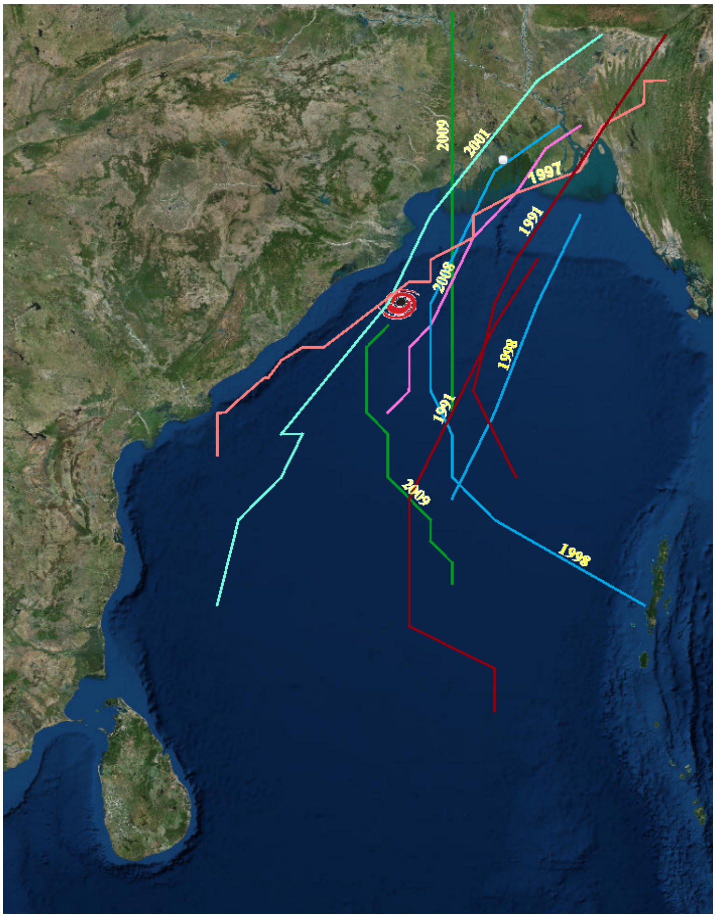


Figure 3. Historical cyclone tracks over the GB delta for the period of 20 years

The WRF model is integrated for 96 hours using Final analysis data with 6 hourly lateral boundary conditions. The model initial condition is taken at 00:00 UTC on 23 May 2009. The figure-2 represents the model simulated surface wind speed (m/s) and wind vector valid at 06:00 UTC on 23 May, 24 May, 25 May and 12:00 UTC on 25 May 2009. It is observed that the cyclonic structure at a different time is reasonably well represented in the model and the movement of the storm is also well simulated. From results, it is seen that the movement of the storm is faster that the observations. In model simulation the storm crossed the coast at

03:00 UTC on 25 May 2009. The observed maximum surface wind is about 31 m/s at 09:00 UTC on 25 May 2009 and the simulated maximum surface wind is reasonably well captured in the model. Historical cyclone tracks over the GB delta for the period of 20 years and Model simulated surface wind speed (m/s) and wind vector at different time period is illustrated in Figure 3 and 4.

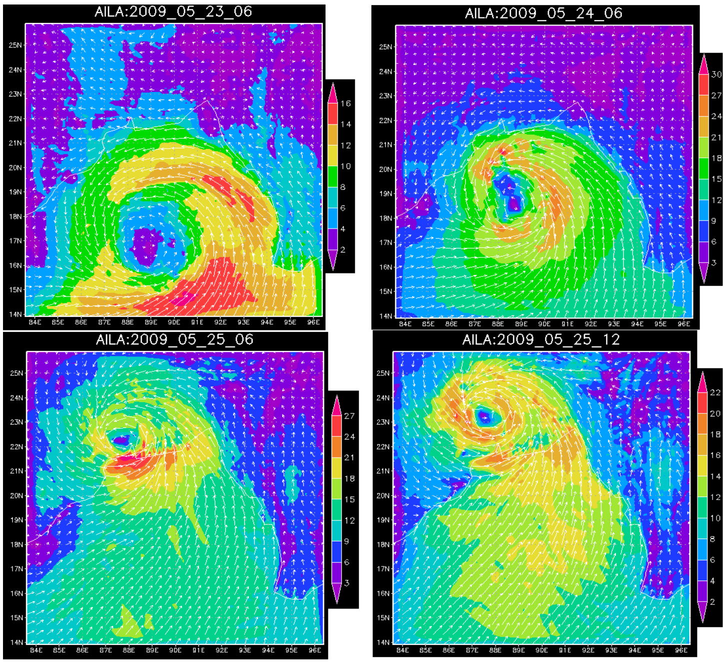


Figure 4. Model simulated surface wind speed (m/s) and wind vector at different time period

3. Hydrodynamic model

The hydrodynamic (ADCIRC) model also has been simulated using the external forcing parameters such as tides and river discharge. The model has been run with normal river flow (<1000 m^3/sec) and tidal forcing at the open boundary in the ocean. It resulted that the water level is varied between ≈ 0.2 -0.5 m above the mean sea level (MSL) in the Hooghly River. There are no significant non-linear interaction has been observed where the river flow meets the tidal currents in the estuary.

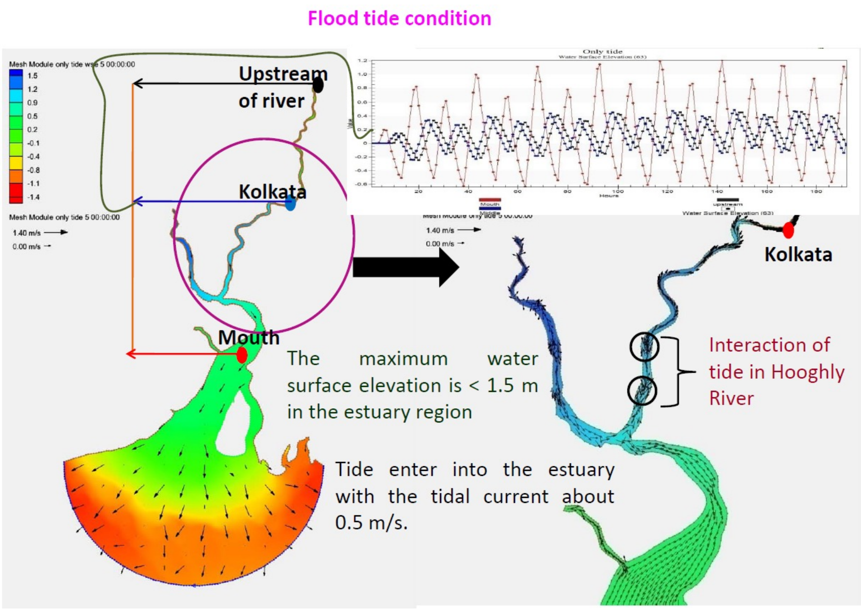


Figure 5. The interaction between upstream river flow and tidal currents during flood tide condition

Similarly, the model has been forced with the extreme river discharge flow (>3000 m^3/sec), tides as an open boundary forcing parameter and storm wind speed as a surface forcing to understand the water level variation and circulation features in the Hooghly estuary and River. The results of the model simulations showed that the water level is increased approximately 1 – 2 m above the MSL in the Hooghly River. There is a significant non-linear interaction has been observed in the meeting region of the river flow and tidal currents due to the tidal forcing. The illustration case study has shown in the below figure 5 and 6.

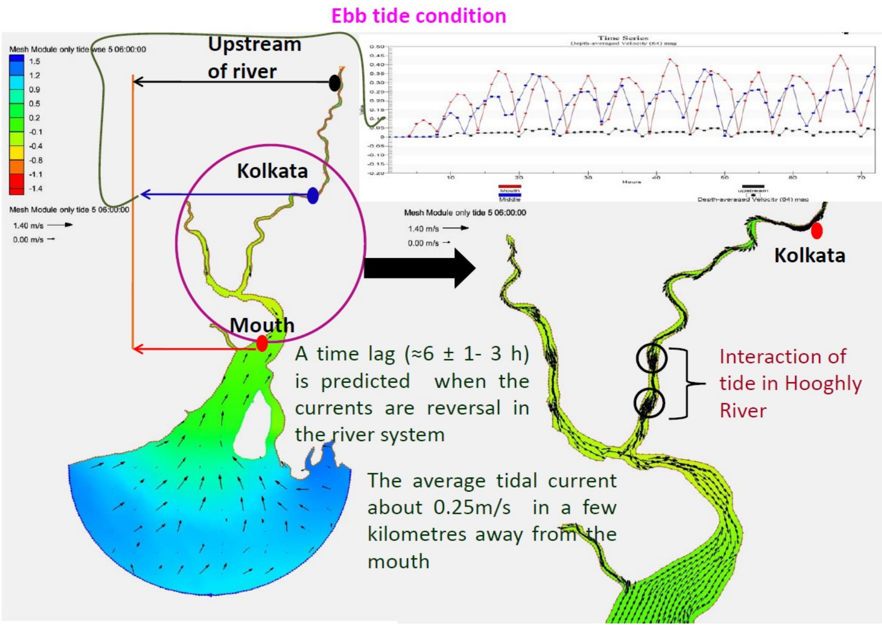


Figure 6. The interaction between upstream river flow and tidal currents during ebb tide condition

Future Work plan (2015-2016)

In the coming year 2016-17, the following tasks shall be carried out for the Ganges Deltaic research study.

S. No	Ongoing Tasks	Nature of the work
1	River discharge estimations will be carried out various river locations at Hooghly River.	Field survey
2	Deployment of various oceanographic field equipment for the validation of sediment dynamics	Field based
3	Finalization of the bathymetric survey at selected locations at Hooghly River (ongoing)	Field based
	Validation of the predictions derived from the Advance Circulation Model (ADCIRC) of the Hooghly river-estuary	Experimental/ Field based/ Modelling
4	Validation of the extreme weather prediction model over the GB delta	Experimental/ Field based
5	Ground water sampling to understand the salinity intrusion in the	Field based

	lower delta region	
6	Prediction of peak surge and inundated areas in and around the Hooghly river during the cyclonic storm and its effect in the climate change scenarios	Experimental/ Field based/ Modelling
7	Assessment of Mangrove cover change using GIS and remote sensing followed by field based validations (through Aerial photography)	GIS based/ Field survey
8	Contribute to prepare the Global Delta Vulnerability Index for Ganges Delta, India.	Analytical
9	Stakeholder consultations for understanding various issues of local community	Field survey

Finally it proposes to assess the influences of rapid urbanization, institutional and infrastructural vulnerability to changes in the production systems. The intention is to create a synthesis of the biological risks and socio-economic vulnerability factors at regional scale.

Publication:

Dennis P Swaney; Bongghi Hong; Paneer Selvam; Robert W Howarth; Ramachandran Ramesh; Purvaja Ramachandran (2015), Net Anthropogenic Nitrogen Inputs and Nitrogen Fluxes from Indian Watersheds: A Preliminary Assessment, *Journal of Marine Systems,* vol. *141*, 45-58.

IV. Other Accomplishments

BF DELTAS dinner meeting at the AGU Fall Meeting December 17, 2015 in San Francisco, California.

The participants include PIs Efi Foufoula-Georgiou, Eduardo Brondizio, Irina Overeem, Steven Goodbred Jr., Fabrice Renaud, Yoshiki Saito, Robert Nicholls; members Zita Sebesvari, Carol Wilson, Atilla Lazar, Anthony Longjas, Alejandro Tejedor, Stephanie Higgins, Rachel Bain, Ravi; members of affiliated project ESPA: Paul Whitehead, Derek Clarke, Craig Hutton; and Jonathan Gilligan (Vanderbilt University).

Stakeholder workshops on the Amazon delta on May 2 – 10, 2016 in Brazil

Stakeholder meetings took place in the municipalities of Soure, Macapá, Gurupá and Belém. It was organized by BF Deltas PI and members: Andressa Vianna Mansur, Eduardo Brondizio (Indiana University) and Dr. Michael Hagenlocher and Dr. Zita Sebesvari (UNU-EHS) – with collaboration of local researchers: in Soure: Vivian Zeidemann (UFPA – Federal University of Belém – Belém); in Belém: Ricardo Fialho (SIPAM – System for the Protection of the Amazon); in Macapá: Luis Roberto Takiyama (IEPA - Institute for Scientific and Technological Research of the State of Amapá, Centre for Water Research – Macapá); and in Gurupá: Lucy Miller (PhD student in Anthropology at Indiana University). A total of 50 participants were involved: Soure: 11; SIPAM-Belem: 7; Macapa: 13; Gurupa: 5 and Belem: 14.

Main Topics:

1. Present the results of the risk and vulnerability assessments and its elements for the Amazon delta to different stakeholders.
2. Discuss the outcomes, collect targeted feedback and occasionally also additional data for the construction of the GDVI (Global Delta Vulnerability Index) and other collaboration papers.

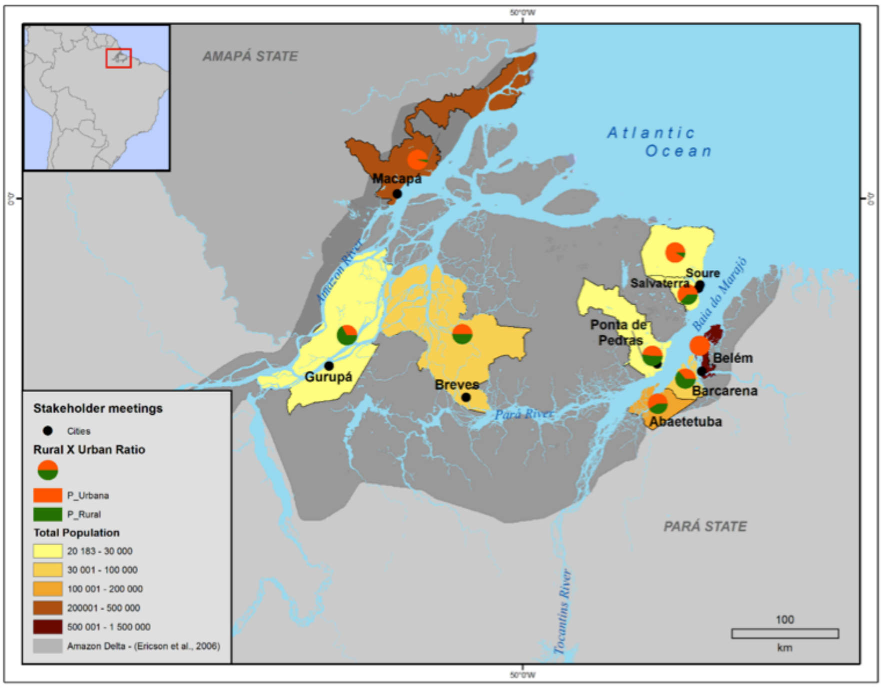


Figure 1. Cities for stakeholder meetings.

Figure 2. Organziers and particpants in the stakeholder workshops.

Special sessions at major meetings
Organization of *special sessions* at the AGU 2015, EGU 2016 and JpGU 2016 (deltas session) meetings. We have proposed a special session on deltas at the 2016 AGU meeting and the PIs plan to attend and present papers on the Belmont Forum DELTAS project. Special sessions for EGU 2017 and JpGU 2017 are planned right now.

Special Issue in Sustainability Science lead by PIs Fabrice Renaud, Sylvia Szabo, and Zoe Matthews
BF-DELTAS led a special issue of papers in Sustainability Science addressing delta social-ecological systems through multi-disciplinary lenses. "Sustainable Deltas: Livelihoods, Ecosystem Services, and Policy Implications", *Sustainability Science*, Vol. 11, Issue 4, 2016.

1). Brondizio, E.S., N.D. Vogt, A.V. Mansur, E.J. Anthony, S. Costa, and S. Hetrick (2016), A conceptual framework for analyzing deltas as coupled social–ecological systems: an example from the Amazon River Delta, *Sustainability Science*, *11*(4), 591-609.

2). de Araujo Barbosa, C.C., J. Dearing, S. Szabo, S. Hossain, N.T. Binh, D.K. Nhan, and Z. Matthews (2016), Evolutionary social and biogeophysical changes in the Amazon, Ganges–Brahmaputra–Meghna and Mekong deltas, *Sustainability Science*, *11*(4), 555-574.

3). Mansur, A. V., E. S. Brondízio, S. Roy, S. Hetrick, N. Vogt, and A. Newton (2016), An assessment of urban vulnerability in the Amazon delta and estuary: a multi-criterion index of flood exposure, socio-economic conditions and infrastructure, *Sustainability Science*, *11*(4), 625-643, doi: 10.1007/s11625-016-0355-7.

4). Renaud, F. G., S. Szabo, and Z. Matthews (2016), Sustainable deltas: livelihoods, ecosystem services, and policy implications, *Sustainability Science*, *11*(4), 519-523, doi:10.1007/s11625-016-0380-6.

5). Sebesvari, Z., F.G. Renaud, S. Haas, Z.D. Tessler, M. Hagenlocher, J. Kloos, S. Szabo, A. Tejedor, and C. Kuenzer (2016), A review of vulnerability indicators for deltaic social–ecological systems, *Sustainability Science*, *11*(4), 575-590.

6). Szabo S., E. S. Brondizio, S. Hetrick, F. G. Renaud, R. J. Nicholls, Z. Matthews, Z. D. Tessler, A. Tejedor, Z. Sebesvari, E. Foufoula-Georgiou, S. Costa, and J. A. Dearing (2016), Population dynamics, delta vulnerability and environmental change: Comparison of the Mekong, Ganges-Brahmaputra and Amazon delta regions, *Sustainability Science*, *11*(4), 539-554, doi: 10.1007/s11625-016-0372-6.

7). Tessler Z.D., C. J. Vörösmarty, M. Grossberg, I. Gladkova, and H. Aizenman (2016), A global empirical typology of anthropogenic drivers of environmental change in deltas, *Sustainability Science*, *11*(4), 525-537, doi: 10.1007/s11625-016-0357-5.

8). Vogt, N., M. Pinedo-Vasquez, E. S. Brondizio, F. G. Rabelo, K. Fernandes, O. Almeida, S. Riveiro, P. J. Deadman, and Y. Dou (2016), Local ecological knowledge and incremental adaptation to changing flood patterns in the Amazon delta, *Sustainability Science*, *11*(4), 611-623, doi: 10.1007/s11625-015-0352-2.

Invited Synthesis Article published in the journal *Current Opinion in Environmental Sustainability:*

1). Brondizio, E.S., E. Foufoula-Georgiou, S. Szabo, N. Vogt, Z. Sebesvari, F.G. Renaud, A. Newton, E. Anthony, A. V. Mansur, Z. Matthews, S. Hetrick, S.M. Costa, Z.D. Tessler, A. Tejedor, A. Longjas, and J.A. Dearing (2016), Catalysing Action Towards the Sustainability of Deltas, *Current Opinion in Environmental Sustainability*, *19*, 182-194.

Special Issue in *Elementa* on 'Sustainable Deltas':

Deltas account for approximately 1% of global land area but are home to more than 500 million people. Deltas play a key role in agricultural and aquaculture production, food security, and commerce – yet, deltas are amongst the world's most threatened socio-ecological systems, a situation projected to amplify in the 21st century due to both natural and anthropogenic impacts on the environment.

This Special Feature invites contributions that advance research on deltas as complex systems, develop integrated frameworks for delta dynamics modeling, explore quantitative metrics of vulnerability and resilience of social-ecological systems, consider policy and governance issues linked to the sustainable development of deltas, and use in-situ and satellite data for guiding modeling and risk assessment. Analysis of challenges under projected scenarios of change of specific deltas are especially welcome.

Drawing from recent sessions at AGU 2015 and JpGU 2016 conferences and contributing to the International Council of Science "Sustainable Deltas Initiative" this Special Feature aims to promote international scientific collaboration, knowledge and data exchange, and foster science-policy interactions for a sustainable future of threatened deltas.

This Special Feature will be published in the multidisciplinary, nonprofit, open-access journal Elementa: Science of the Anthropocene. The journal pays particular attention to the presentation of research as part of Special Features. You can find examples of Special Features currently in publication here. The journal is known for its excellent author services and wide promotion of published articles.

Deadline for submissions is October 15th, 2016.

We would like to receive your expression of interest with a tentative manuscript title and authors and a short 100 words abstract by June 30th, 2016.

Guest editors:
Irina Overeem, Community Surface Dynamics Modeling System, University of Colorado at Boulder, USA. email: Irina.overeem@colorado.edu
Fabrice Renaud, Institute for Environment and Human Security, United Nations University, Bonn, Germany. email:renaud@ehs.unu.edu
Paola Passalacqua, Dept. of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, USA, email: paola@austin.utexas.edu

Stakeholders and research meeting at the partner institution CUNY, in Sept 12-16, 2016 organized by the group of PI Charles Vorosmarty
The scope of the meeting is threefold: (1) a stakeholders meeting with 2 major stakeholder representatives from each of the three deltas (Mekong, Ganges, and Amazon), (2) science collaboration among PIs towards completing integrative papers on our Belmont Forum multi-disciplinary research, and (3) preparation of a synthesis paper of the BF team for a high impact journal.

PI exchanges and Web collaboration ideas
PI Foufoula-Georgiou presented at the AGU 2015, EGU 2016 and JpGU 2016 meetings and met with BF-DELTAS partners present. The team also conducts regular cyber seminars and meetings for demonstration of modeling tools, discussion of data analysis and other concerns related to the project.

Outreach
We have developed a web site for the project http://www.delta.umn.edu/, which we will update regularly and populate with our publications, presentations, and products.

The results have been disseminated to the communities of interest by:

(1) Publications of the group inform the research communities.

(2) The National Science Foundation (NSF) featured the NSF/Belmont Forum funded Deltas project in recognition of World Oceans Day (http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=138738&org=NSF&from=news).

(3) PI Eduardo Brondizio published an article in the Nature of Cities blog: The Elephant in the Room: Amazonian Cities Deserve More Attention in Climate Change and Sustainability Discussions

(3) News articles that feature work on Profiling Risk and Sustainability in Coastal Deltas of the World

- Washington Post: From the Mississippi to the Ganges, river deltas are in major trouble.
- The Conversation: Delta cities, wealthy or not, face rising risk from sinking land.
- Deltas at Risk: Profiling Risk and Sustainability in Coastal Deltas of the World.

Opportunities for training and professional development provided by the DELTAS project

Training has been provided via all BF-DELTAS activities, in the following categories:

(1) One-to-one mentoring of students and post-docs by BF-DELTAS PIs

(2) Engagement of students, post-docs, and young PIs into interdisciplinary research via the working group meetings and short courses. The project team also holds regular cyber-seminars and meetings for demonstration of modeling tools, discussion of data analysis and other concerns related to the project:

a) Efi Foufoula-Georgiou (University of Minnesota), February 23, 2016
b) John Dearing (University of Southampton), March 1, 2016
c) Zach Tessler (City University of New York), "A global empirical typology of anthropogenic drivers of environmental change in deltas" April 5, 2016
d) Andressa Mansur (University of Indiana, Bloomington), "An assessment of urban vulnerability in the Amazon delta and estuary: a multi-criterion index of flood exposure, socio-economic conditions and infrastructure"April 5, 2016
e) Zita Zebesvari (United Nations University), May 13, 2016
f) Stephanie Higgins (University of Colorado, Boulder), July 12, 2016

(3) Participation of students and postdocs in the Summer Institute on Earth surface Dynamics (SIESD), which in 2016 is on Coupled hydro-eco- geomorphologic processes in human dominated landscapes: cascade of changes and the use of modeling for management and decision making. PIs Efi Foufoula-Georgiou, Irina Overeem, Carol Wilson and Alejandro Tejedor will give lectures on deltas.

(4) Participation of students and post-docs at the AGU 2015, EGU 2016 and CSDMS 2016 meetings where the BF-DELTAS partners meet.

(5) Involving students and post-docs in field monitoring studies in the Mekong, Ganges, and Amazon river deltas as part of the BF-DELTAS project.

In Year 4 (2016-2017), we will plan the following major activities:

(1) An end-of-the-project meeting, as requested by BF, at the 2016 AGU Fall meeting on Dec 10-11, 2016.

(2) We have planned a stakeholders and research meeting at the partner institution CUNY, in Sept 12-16, 2016 organized by the group of PI Charles Vorosmarty. The scope of the

meeting is threefold: (1) a stakeholders meeting with 2 major stakeholder representatives from each of the three deltas (Mekong, Ganges, and Amazon), (2) science collaboration among PIs towards completing integrative papers on our Belmont Forum multi-disciplinary research, and (3) preparation of a synthesis paper of the BF team for a high impact journal.

(3) Increase synergy with LIFE (Linked Institutions for Future Earth) project goals and objectives.

(4) Apply the network-based framework to quantify the complexity of the Ganges Brahmaputra Meghna (GBM), Mekong and Amazon river deltas and assess changes under human and climate stressors.

(5) Public release of the iRODS ("Integrated Rule-Oriented Data System") data server, which is a middleware between (several) physical data storage systems and the user interface and primarily used for organizing and sharing data.

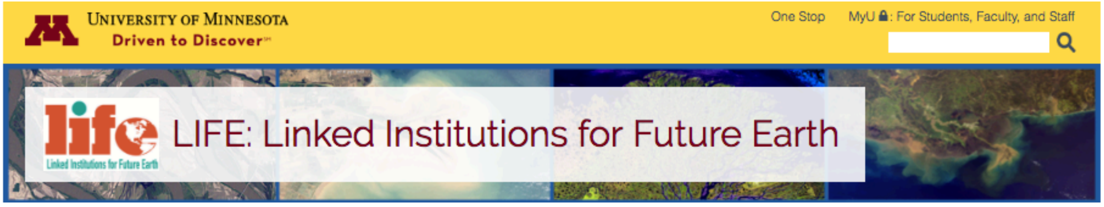
(6) Incorporate into CSDMS's Web Modeling Tool the tools developed for Delta-RADS (e.g., generate GeoTIFFs and shapefiles of datasets for delta modeling; generate hypsometry input files for HydroTrend v.3.0 from the delineated DEM).

(7) Accelerate collaboration with the Ecosystem Services For Poverty Alleviation (ESPA) Deltas project by participating in their final UK event: "The Sustainable Development Goals and Deltas", to be held on November 22-23, 2016.

(8) The BF DELTAS team are coordinating an event, with the Julie Ann Wrigley Global Institute of Sustainability, on *River deltas at the crossroads: transformative change for people and ecosystems* that will be held at the IUCN Water Pavilion, September 2, 15.30-16.30, during the IUCN World Conservation Congress in Hawaii.

V. Affiliated Projects

LIFE (http://life.umn.edu/)
(Foufoula-Georgiou)



LIFE, or Linked Institutions for Future Earth, aims to create an international network of researchers, institutions, and experimental sites/field observations dedicated to advancing the quantitative predictive understanding of the Earth surface system. LIFE is a **Virtual Institute**, sponsored by the National Science Foundation (NSF) Science Across Virtual Institutes (SAVI) program, working to catalyze global research activities efficiently and economically while mentoring and creating international research opportunities for junior researchers.

The objectives of LIFE include:

1. Creating a global network of leading institutions to understand and predict the evolution of the Earth-surface environmental under natural and human-induced change;

2. Cultivating a culture of action-oriented research; and

3. Creating a forum for sharing data, ideas, and expertise while mentoring young researchers within a global interdisciplinary environment.

WISDOM PROJECT (http://www.wisdom.caf.dlr.de/en)
(Kuenzer)

Challenges in the Mekong Delta Area

The Mekong Delta in Vietnam offers natural resources for several million inhabitants. However, a strong population increase, changing climatic conditions and regulatory measures at the upper reaches of the Mekong lead to severe changes in the Delta. Therefore, decision makers, planners and local authorities have to face new challenges. Extreme flood events occur more frequently, drinking water availability is increasingly limited, soils show signs of salinization or acidification, species and complete habitats diminish. All these problems call for an optimized, integrated resource management. For this purpose detailed knowledge and hydrologic,-, hydraulic-, ecologic-, and sociologic factors must be available. Furthermore, the cooperation of national institutes as well as national, regional and local authorities needs to be strengthened.

Goal of the Project

It is the goal of WISDOM to jointly (Vietnamese and German partners) design and implement an Information System for the Mekong Delta, containing information from the fields of hydrology, sociology, information technology and earth observation. The integration of such data will enable the end-user of the system to perform analyses on very specific questions; and thus will supply the end-user with a tool supporting regional planning activities.

Approach

The design of the system puts the focus on the constant integration of available and newly generated data from all different disciplines. This enables user-oriented analyses and custom designed querying to develop sustainable solutions in the field of resource management. Possible applications of the system are:

- Monitoring of floods and droughts
- Evaluation of flood and drought risk, damage potential and actual damages
- Analyses of water quality, pollution and sediment load
- The improvement of flood prediction via remotely sensed precipitation information
- Detailed adaptation of surface and sub-surface discharge models
- Information of landcover- and landuse changes
- Observation of settlement development, surface sealing and population growth

DELIGHT

Delta Information System for Geoenvironmental and Human Habitat Transition

DELIGHT PROJECT (http://www.delight.eoc.dlr.de/en)
(Kuenzer)

Challenges in the Yellow River Delta Area

Within the Yellow River Delta, economic development as well as high urbanisation rates on the one hand are accompanied by necessary conservation of natural resources on the other hand – a situation that induces several areas of conflict. The potential conflicts and the clearly existing need for actions are explicitly described in the "Yellow River Delta Development Plan" (Government of the province Shandong, 2009). The region is explicitly mentioned in the national tenth and eleventh five-year plan, and shall become a model region for an ecologically-economically compliant circular-flow-economy. According to the development plan 2009 published by the Shandong Government, it is intended to establish a modern, ecological and efficient development model until 2015.

Objectives of the DELIGHT Project

Objective of the DELIGHT project is to support the efforts of local stakeholders within the Yellow River Delta to implement the development plan for the delta in the upcoming years, to assist and provide the necessary information tailored to the needs of the important stakeholders in order to substantially support their planning processes.

Major research topics and tasks addressed in DELIGHT
In the context of the project DELIGHT, research questions concerning the following fields are addressed and answered:

- Environmental monitoring and dynamics of the Yellow River Delta and lower reaches
- Water quality and pollution threats
- Hydro- and morphodynamics, ground water and flood risks
- Trends and risks of urbanisation
- Capacity development and training
- Information system design and data integration

Comprehensive recommendations and guidelines for actions are derived from findings and will be made available for Users and Stakeholders.

Goals of the DELIGHT Project

Goal of the DELIGHT project and its large Sino-German consortium is to jointly contribute to climate protection, Integrated Land-, Water and Coastal Zone Management (ILWRM, ICZM) and the development of innovative services and technologies in the Yellow River Delta (YRD). This will be reached through joint research and engineering in multidisciplinary fields from natural- as well as socio-economic science, the development of adaptation strategies, as well as the design and implementation of the "Delta Information System for Geoenvironmental and Human Habitat Transition": DELIGHT.

espa
ecosystem services for poverty alleviation

ESPA PROJECT (http://www.espa.ac.uk/)
(**Nicholls, Matthews**)

ESPA research focuses on three key regions:

- **Africa**
- **Asia**
- **South America**

Each of these regions face significant challenges in managing ecosystem services in the context of poverty alleviation and sustainable growth, which ESPA aims to address.

ESPA Situational Analyses

Working for ESPA, international research consortia previously undertook four regional and two thematic situation analyses both to identify the key ecosystem service challenges and to propose the best ways of addressing them — through research to alleviate poverty. Each consortium was made up of researchers from the region, the United Kingdom and elsewhere, in collaboration with national governments and local partners

BanglaPIRE PROJECT (http://www.banglapire.org)
(**Goodbred Jr.**)

Project Summary

Just as several great rivers, the Brahmaputra, Ganges and Meghna, converge in Bangladesh, so do opportunities for science, education and societal improvements in this densely populated nation. These rivers deposit their 1 Gigaton/year of sediment at the rapidly subsiding junction of three tectonic plates to form the Ganges-Brahmaputra-Meghna Delta (GBMD), the world's largest. The rapid subsidence favors preservation of high-resolution records of the GBMD's dynamic fluvial processes, the tectonics of its growing accretionary prism, and the development of a new convergence boundary. Opportunities abound for a better understanding of fundamental interactions between sedimentation and tectonics, and also of the hazards from earthquakes, river avulsion and flooding facing the 150+ million inhabitants of the GBMD.

Scientific Overview

This project applies a multidisciplinary approach to investigating a set of interrelated processes affecting the GBMD. The central theme is the sediments and stratigraphic architecture of the evolving GBMD as a record of fundamental fluvial and tectonic processes, and feedbacks between them. Drilling of ~250 scientific wells by a local low-cost technique supplemented by mechanized drilling at key sites will provide a detailed ground-truthed stratigraphy. A suite of other measurements will augment this record. Electrical resistivity profiles and marine multichannel seismic reflection along rivers and flooded areas will image subsurface features and correlate between wells. Two nested-well arrays with fiber optic cables will monitor compaction. A seismic network will record local seismicity and teleseismic phases to characterize active faults and regional crustal structure. A GPS network will monitor horizontal and vertical strain. Outcrop geology of deformed Neogene strata will augment subsurface data.

Scientific targets

1) Subduction tectonics within the GBMD and sources of future earthquakes. Buried by recent sedimentation and continually changing, the plate boundary geometry and deformation are undefined.
2) The forward jump of India-Asia convergence from the eastern Himalayas to the Shillong Plateau, an astonishing geologic event. The focus is on the new frontal fault developing as a blind structure buried in Bangladesh.
3) Very rapid GPS subsidence rates, which exceed geologic rates as well as sea-level rise. The strategy is to distinguish long-term (sediment loading, tectonics, compaction) and transient components (earthquake, anthropogenic).
4) Channel avulsions of the Ganges and Brahmaputra rivers. Rapid subsidence has helped preserve complete fluvial sequences that can be linked to individual rivers by unique geochemical fingerprints.
5) Integrated basin behavior and evolution: coupling tectonics to fluvial processes, and integrating long-term steady processes with abrupt, short-term events.