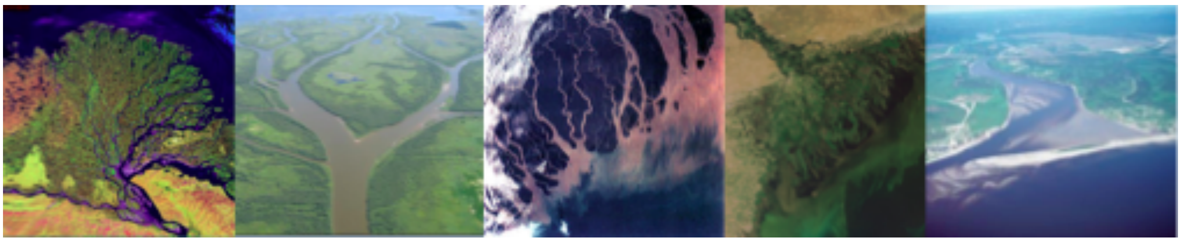
Belmont Forum-G8 Collaborative Research:

BF-DELTAS:

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

Award Number: 1342944

Year 2 Progress Report: 2014–2015



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1. BF-DELTAS: Scope and Objectives Overview

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):

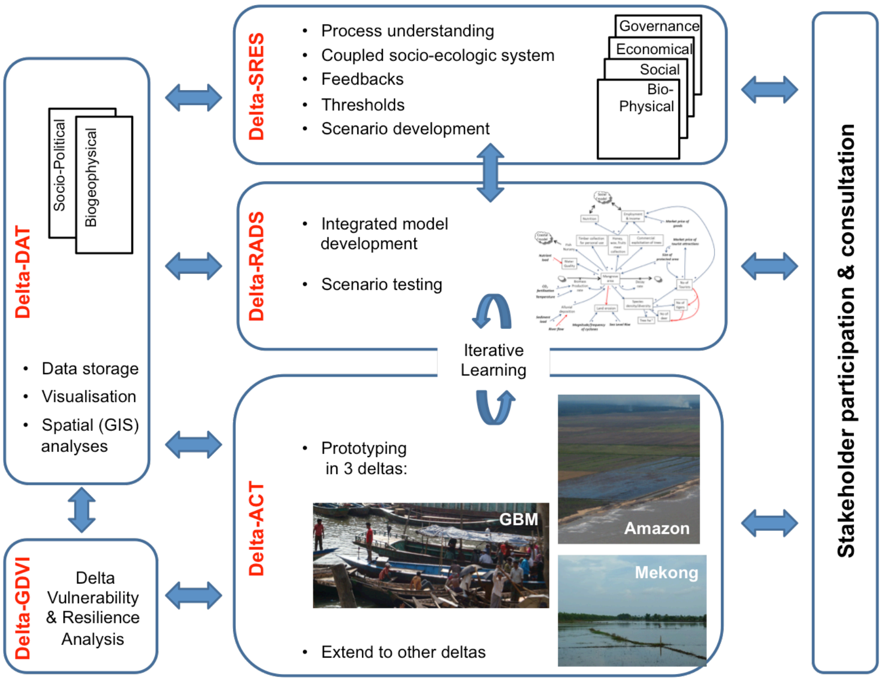
- **Delta-SRES**: *Develop a theoretical framework for assessing delta vulnerability and the possibility for transitions to undesired biophysical or socio-economic states under various scenarios of change.* Delta-SRES will, therefore, advance sustainability science for deltas.

- **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.

- **Delta-DAT:** *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.

- **Delta-GDVI**: *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

- **Delta-ACT:** 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?

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

2. Timeline and Project Organization

THEME	MAIN ACTIVITY TYPE	2013				2014				2015				2016		
		Jan Mar	Apr Jun	Jul Sep	Oct Dec	Jan Mar	Apr Jun	Jul Sep*	Oct Dec	Jan Mar	Apr Jun	Jul Sep	Oct Dec	Jan Mar	Apr Jun	Jul Sep**
Project Management	Pre-project meetings at conferences (individual PI's)	1	2	3												
	Annual meetings				4 Green		TF	5 Green				6				7
	Development of Strategic Implemtation Plan (SIP)			VL	VL											
	Annual review of actual deliverables compared to expected deliverables from SIP							TF								
Delta-SRES Foufoula-Georgiou/ Dearing	Develop theoretical framework for understanding role of environmental change on deltas through compilation/historical analysis of available data (focusing on ecogeomorphology/climate and delta function; human influences)			WO	WO	WO	TF	TF								
	Develop analytical tools to examine interactions between baseline data (above) for ecological components, ecological processes, ecosystem services, and human effects						TF	TF								
	Apply tools to integrative modeling using baseline (above) and current/projected future conditions															
	Present policy recommendations to stakeholders															
Delta-RADS Overeem / Matthews	Compile existing social, economic, bio-physical and ecosystem services data			WO	WO	WO	TF	TF								
	Develop an infrastructure for gathering new data for data poor areas					WO	TF	TF								
	Gather new data for data poor areas							TF								
	Develop open-source GIS modeling system					TF	TF	TF								
	Develop Delta Modeling toolbox in CMT						TF	TF								
	Run simulations with key delta process models							TF								
	Scenario testing: application of modeling framework to regional planning															
	Training courses to disseminate Delta-RADS: coincide with annual meeting															
Delta-DAT Brondizio / Vorosmarty / Saito	Identify priority regions for data compilation (delta fingerprinting system to identify delta hotspots			WO	WO											
	Prepare and sign agreements for data		VL	VL	VL											
	Develop IT infrastructure to support data repository			WO	WO	TF										
	Assimilate data sets across spatial and thematic scales				WO	TF	TF	TF								
	Data User Workshop/Training courses to guide development and disseminate Delta-DAT							TF								
Delta-GDVI Renaud / Sebesvari	Selection and adaptation of a theoretical framework				WO	TF										
	Identification and evaluation of a preliminary set of indicators (partitipatory field research, literature analysis, stakeholder discussions)					WO	TF	TF								
	Integrate information from remote sensing data					WO	TF	TF								
	Development of a composite indicator for delta vulnerability (sub-Delta assessment - Delta-ACT							TF								
	Development of GIS maps and validation of the composite indicator in Delta-ACT															
	Compilation of data for world deltas															
	Global Delta vulnerability and analysis															
Education products	Integrate research program into graduate experience/training (eg. CUNY-CREST)							TF								
	Prepare online educational materials															
Delta-ACT (all sites) Harrison / Goichot	Identify regional experts for GBM, MRD and AMD case study sites		Green	Green	Green											
	Develop a composite indicator for delta vulnerability for GBM, MRD and AMD case study sites				WO	WO	TF	TF								
	Apply tools/models to identify delta condition and develop responses for GBM, MRD and AMD case study sites				WO	WO	TF	TF								
	Present policy recommendations to stakeholders, for GBM, MRD and AMD case study sites															
Delta-ACT (GBM) Goodbred	Collate and correct SRTM topographic data and adjust to local cartographic and topographic datasets		WO	WO	WO	WO	TF	TF								
	Collect census data for economic, social, and demographic variables and associate to geospatial data platform		WO	WO	WO	WO	TF	TF								
	Assimilate data on flooding and sediment aggradation; habitat modification; climate change effects; demographics and socio-economics			WO	WO	WO	TF	TF								
	Map ecosystem dynamics (derivation from satellite imagery - mangrove decline, coastline changes, and urban sprawl)			WO	WO	WO	TF	TF								
	Assimilate data on ecosystem dynamics				WO	WO	TF	TF								
Delta-ACT (Mekong) Kuenzer	Collate accurate data from MRC on the state of the basin in terms of sediment discharge and hydrology			WO	WO	WO	TF	TF								
	Collate and correct SRTM data from local topographic datasets to obtain a complete topographic coverage of the delta necessary for evaluation and modeling of the impacts of future sea-level rise			WO	WO	WO	TF	TF								
	Collect census data for economic, social, and demographic variables and associate to geospatial data platform			WO	WO	WO	TF	TF								
	Determine recent and current rates of sediment accumulation in the flood plain and delta plain using Pb-210 and Cs-137			WO	WO	WO	TF	TF								
	Map changes and delta dynamics in land-use, mangrove forest cover, coastline, aquaculture expansion and urban expansion from hyper-temporal and multi-sensor satellite imagery				WO	WO	TF	TF								
	Map and analyze flood pattern progression from satellite image time series				WO	WO	TF	TF								
	Identify recent channel morphodynamic and sediment balance changes in the delta from analysis of channel morphometric data and satellite imagery			WO	WO	WO	TF	TF								
	Identify topographical change of inter to subtidal flats on eastern coast			WO	WO	WO	TF	TF								
	Identify delta shoreline morphodynamics, sediment dynamics, and status (advance, stability, retreat) over the entire delta shoreline using high-resolution satellite imagery completed by ground-truthing			WO	WO	WO	TF	TF								
	Identify and model the role of anthropogenic activities and their potential effects			WO	WO	WO	TF	TF								
	Model and map delta vulnerability to scenarios of climate change and sea-level rise			WO	WO	WO	TF	TF								
	Collate data on distribution, threats, conservation actions, risk of extinction, utilization and and livelihoods values of focal taxonomic groups in the Mekong data			WO	WO	WO	TF									
	Review Mekong delta biodiversity data and input to IUCN Red List															
	Explore linkages with Conservation International Lower Mekong projects			Green	Green			TF								
	Develop geospatial model for assessment of threats to delta fishes					WO	WO	WO								
	Conduct a desktop analysis of the socio-economic value derived from the fishes of the Mekong delta region															
Delta-ACT (Amazon) Brondizio	Planned yearly field research and meeting with regional collaborators						TF									
	Collate and correct SRTM topographic data and adjust to local cartographic and topographic datasets		WO	WO	WO	WO	TF	TF								
	Collect census data for economic, social, and demographic variables and associate to geospatial data platform		WO	WO	WO	WO	TF	TF								
	Collect land cover data, satellite imagery, available ecological data		WO	WO	WO	WO	TF	TF								
	Assimilate data on flooding and sediment aggradation; habitat modification; climate change effects; demographics and socio-economics			WO	WO	WO	TF	TF								
	Map changes in land-use and mangrove cover from satellite imagery				WO	WO	TF	TF								
	Map ecosystem dynamics (derivation from satellite imagery - biomass changes, mudflat dynamics				WO	WO	TF	TF								
	Assimilate data on ecosystem dynamics				WO	WO	TF	TF								
	Present policy recommendations to stakeholders															

TF - Thinking Forward; WO - Working ON; VL - Very Late

[1] Changing Coasts and Climate, March 2013; Mekong Environmental Symposium, March 2013;[2] AGU Coastal Processes, Texas, 2013; EGU Annual meeting, Austria 2013.[3] IUGG Gothenberg conference and Deltas Symposium, July 2013. [4] Kick-off meeting, December 2013, U.S. University of Minnesota. [5] Mekong, September 2014. [6] Bangladesh, September 2015. [7] Project completion meeting, Europe, August 2016.

3. Projects reported and Integration under the 5 Work Packages (WP)

The Principal Investigator (PI) contributions attached are on:

1. A new Algorithm for Improved Satellite Rainfall Retrieval over Snow-Covered Land Surfaces and Coastal Zones (Foufoula–Georgiou)
2. Delta channel network topology and dynamics for delta comparison, physical inference and vulnerability assessment (Foufoula–Georgiou)
3. GIS delta data for model simulations (Overeem)
4. Ganges-Brahmaputra delta study using the new service components (Overeem)
5. Data Acquisition and Processing (Brondizio)
6. Deltas-DAT support for manuscript preparation and data visualization (Brondizio)
7. Utilization of the iRODS server and iDROP interface (Brondizio)
8. Automatic processing of high-resolution optical remote sensing data (Kuenzer)
9. Land cover classification for the Ganges-Brahmaputra river delta (Kuenzer)
10. Environmental Stress and Vulnerability analysis (Vorosmarty and Tessler)
11. Environmental Stress Typology (Vorosmarty and Tessler)
12. Precipitation and surface inundation patterns (Vorosmarty and Tessler)
13. Development of a theoretical framework (Renaud and Sebesvari)
14. Review of vulnerability indicators used in the three model deltas (Renaud and Sebesvari)
15. Identification of indicators by stakeholders in all three model deltas (Renaud and Sebesvari)
16. Bedload extraction within the G-B River delta—co-location with topography and the backwater (Goodbred Jr.)
17. Natural and Human-Induced Changes in G-B Tidal Channel Network (Goodbred Jr.)
18. Fluvial-Tidal Land surface and hydrodynamics at Natural vs Poldered Areas (Goodbred Jr.)
19. Shoreline changes in the Mekong delta (Anthony)
20. Suspended particulate matter dynamics at the mouth of the Amzon and downdrift mangrove changes on the Amazon-Orinoco coast (Anthony)
21. Shoreline changes in the Ganges-Brahmaputra delta (Anthony)
22. Collation and correction of SRTM topographic data and adjustment to local cartographic and topographic datasets in deltas (Ramesh)
23. Collection of census data for economic, social, and demographic variables and association to geospatial data platforms for deltas (Ramesh)
24. Assimilation of data on flooding and sediment aggradation; habitat modification; climate change effects; demographics and socio-economics (Ramesh)
25. Map ecosystem dynamics (derivation from satellite imagery - mangrove decline, coastline changes, and urban sprawl) (Ramesh)
26. The bio-physical, ecological, geomorphology, and climate data from the Gangetic delta region collected and compiled in a IT-enabled GIS modelling platform (Ramesh)
27. Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

WP1: Delta-SRES (Lead PIs: Efi Foufoula-Georgiou, John Dearing)

- A new Algorithm for Improved Satellite Rainfall Retrieval over Snow-Covered Land Surfaces and Coastal Zones (Foufoula–Georgiou)
- Delta channel network topology and dynamics for delta comparison, physical inference and vulnerability assessment (Foufoula–Georgiou)

WP2: Delta-RADS (Lead PIs: Irina Overeem, Zoe Matthews)

- GIS delta data for model simulations (Overeem)
- Ganges-Brahmaputra delta study using the new service components (Overeem)
- Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

WP3: Delta-DAT (Lead PIs: Eduardo Brondizio, Charles Vorosmarty, Yoshiki Saito)

- Data Acquisition and Processing (Brondizio)
- Deltas-DAT support for manuscript preparation and data visualization (Brondizio)
- Utilization of the iRODS server and iDROP interface (Brondizio)
- Automatic processing of high-resolution optical remote sensing data (Kuenzer)

WP4: Delta-GDVI (Lead PIs: Fabrice Renaud, Zita Sebesvari)

- Environmental Stress and Vulnerability analysis (Vorosmarty and Tessler)
- Environmental Stress Typology (Vorosmarty and Tessler)
- Precipitation and surface inundation patterns (Vorosmarty and Tessler)
- Development of a theoretical framework (Renaud and Sebesvari)
- Review of vulnerability indicators used in the three model deltas (Renaud and Sebesvari)
- Identification of indicators by stakeholders in all three model deltas (Renaud and Sebesvari)

WP5: DELTA-ACT (Lead PIs: Ian Harrison, Marc Goichot)

Delta-ACT Ganges: Steven Goodbred Jr.

- Bedload extraction within the G-B River delta—co-location with topography and the backwater (Goodbred Jr.)
- Natural and Human-Induced Changes in G-B Tidal Channel Network (Goodbred Jr.)
- Fluvial-Tidal Land surface and hydrodynamics at Natural vs Poldered Areas (Goodbred Jr.)
- Ganges-Brahmaputra delta study using the new service components (Overeem)
- Shoreline changes in the Ganges-Brahmaputra delta (Anthony)
- Land cover classification for the Ganges-Brahmaputra river delta (Kuenzer)
- Collation and correction of SRTM topographic data and adjustment to local cartographic and topographic datasets in deltas (Ramesh)
- Collection of census data for economic, social, and demographic variables and association to geospatial data platforms for deltas (Ramesh)
- Assimilation of data on flooding and sediment aggradation; habitat modification; climate change effects; demographics and socio-economics (Ramesh)
- Map ecosystem dynamics (derivation from satellite imagery - mangrove decline, coastline changes, and urban sprawl) (Ramesh)
- The bio-physical, ecological, geomorphology, and climate data from the Gangetic delta region collected and compiled in a IT-enabled GIS modelling platform (Ramesh)
- Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

Delta-ACT Mekong: Claudia Kuenzer

- Automatic processing of high-resolution optical remote sensing data (Kuenzer)
- Shoreline changes in the Mekong delta (Anthony)
- Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

Delta-ACT Amazon: Eduardo Brondizio

- Definition of Amazon Delta/Estuary study site (Brondizio)
- Suspended particulate matter dynamics at the mouth of the Amazon and downdrift mangrove changes on the Amazon-Orinoco coast (Anthony)
- Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

4. Principal Investigator Reports

Integrated Work Package 1: Sustainability science of deltas as coupled socio-ecological systems (Delta-SRES)

Delta environments are complex systems integrating multiple nested spatial and temporal scales, and are subject to multiple drivers of change. While links between environment, ecosystem services, and human well-being are widely asserted [*Cinner et al.*, 2009; *Vo et al.*, 2012], these relationships are poorly understood in deltaic environments, despite the fact that they would form the basis of any sustainability initiative for these important systems. Hence the objective of this Integrated Work Package is to advance sustainability science for deltas (Delta-SRES) by developing the required, theoretical framework for assessing delta vulnerability and the possibility for transitions to undesired biophysical or socio-economic states under various scenarios of change. The work for Delta-SRES has been led by the University of Minnesota (UMN). Their research efforts have concentrated on two main areas: (1) a new algorithm for improved satellite rainfall retrieval over coastal zones and (2) transport and vulnerability in river deltas: a graph-theoretic approach. Application of the developed frameworks will be performed in the Mekong, Ganges, and Amazon river deltas, which are the focal study sites for the DELTAS project (see Integrated Work Package 5: Delta-ACT). However, the developed frameworks are general and transferable to other deltas.

Integrated Work Package 2: Development of Delta Risk Assessment and Decision Support Framework (Delta-RADS).

Modeling is the essential tool for understanding complex systems such as deltas. Hence the objective of this Integrated Work Package is to co-develop, in close collaboration between scientists and stakeholders, an open-access, science-based, integrative modeling framework. The first phase of developing this framework has been to build on the infrastructure of the Community Surface Dynamics Modeling System (CSDMS) lead by the University of Colorado at Boulder (UCB). The UCB team has integrated studies of remote-sensing data with in-situ data and numerical modeling to define sedimentation patterns and subsidence in deltaic lowlands (Yellow River, China, Indus Delta, Pakistan, and Ganges Brahmaputra Delta, Bangladesh). The developed models are being integrated into an open-source, freely available web-based modeling framework being developed by CSDMS. Application of the developed modeling framework will be performed in the Mekong, Ganges, and Amazon River deltas, which are the focal sites for the DELTAS project (see Integrated Work Package 5); however, the developed frameworks are general and transferable to other deltas.

Integrated Work Package 3: Delta International Data Repository (Delta-DAT).

Although relevant datasets for regional delta studies are available in many forms, they are widely dispersed and thus provide limited utility for researchers and end-users. Hence the objective of this Integrated Work Package is to consolidate and make readily available relevant data on bio-physical, social, and economic parameters (Delta-DAT), which can be used by the community at large to assess critical parameters, compute vulnerability metrics, and provide input data to the Deltas-RADS modeling framework. The Indiana University (IU) team developed an initial data needs assessment. They created a Delta-DAT prototype database spreadsheet to assist with data needs assessment and acquisition of bio-physical and socio-economic datasets that will be important for Delta-DAT, and useful for the DELTAS research teams at large. This spreadsheet was shared with the group for review and comments/input. Based on the recommendations of the needs assessment, the IU team have developed and concluded a Delta-DAT module for the Amazon delta area, including the collection and integration of comprehensive multi-temporal biophysical and social data in a Geographic Information Systems (GIS) (see Integrated Work Package 5).

The German Aerospace Center and the University of Wurzburg have been seeking out existing data sources that provide information for the three project's focus regions (see Integrated Work Package 5), for integration into Delta-DAT. Eleven datasets have been compiled so far. To assure that these datasets are readily accessible they are provided in a common data format such as Tiff or shape file. These datasets also contribute to the tasks in the Delta-ACT work package.

The team at CUNY Environmental CrossRoads Initiative has designed and implemented a plan for a shared, and potentially distributed, data storage and distribution system that meets the objectives of Delta-DAT.

Integrated Work Package 4: Development of Global Delta Vulnerability Indices (Delta-GDVI)

Globally, several risk, resilience and/or vulnerability indices have already been developed with different spatial resolutions. However, no comprehensive "vulnerability profile" metrics currently exist that are spatially explicit at high spatial resolutions for deltas, even though profound spatial variability exists in all delta systems critically affecting the ability for successful local decision-making. Thus, the objective of this Integrated Work Package is to develop an integrated set of indices that capture the current and projected physical-social-economic status of deltas around the world ("delta vulnerability profiles"), which will serve to identify and support the critical needs and priorities for research, funding, and action. In the second year of the Belmont Forum funded project, the United Nations University and City University of New York have collaborated in leading the development of the GDVI.

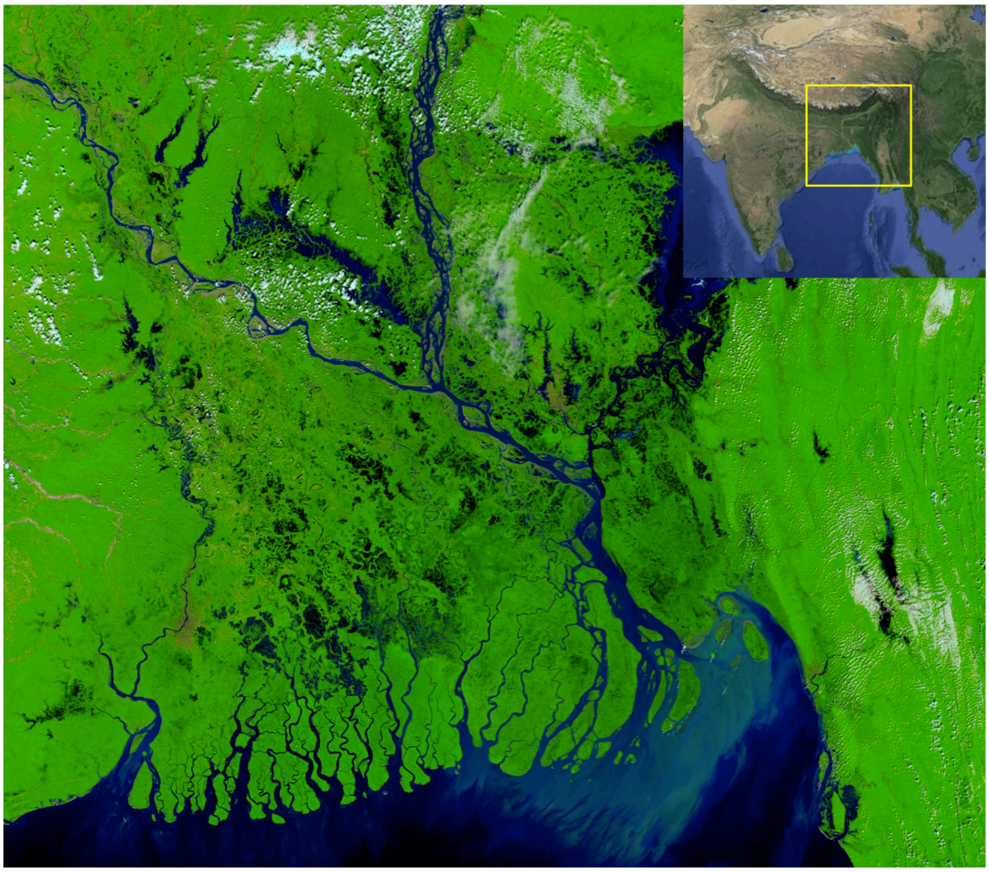
Integrated Work Package 5: Regional Implementation Case Studies (Delta-ACT)

The Delta-ACT component of the project seeks to apply the framework of Delta-SRES, Delta-RADS, Delta-DAT, and Delta-GDVI to three diverse, globally significant delta systems in which the research team has extensive experience and connections with the local community. The case study sites are: the Ganges-Brahmaputra-Meghna (GBM), Mekong, and Amazon deltas.

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

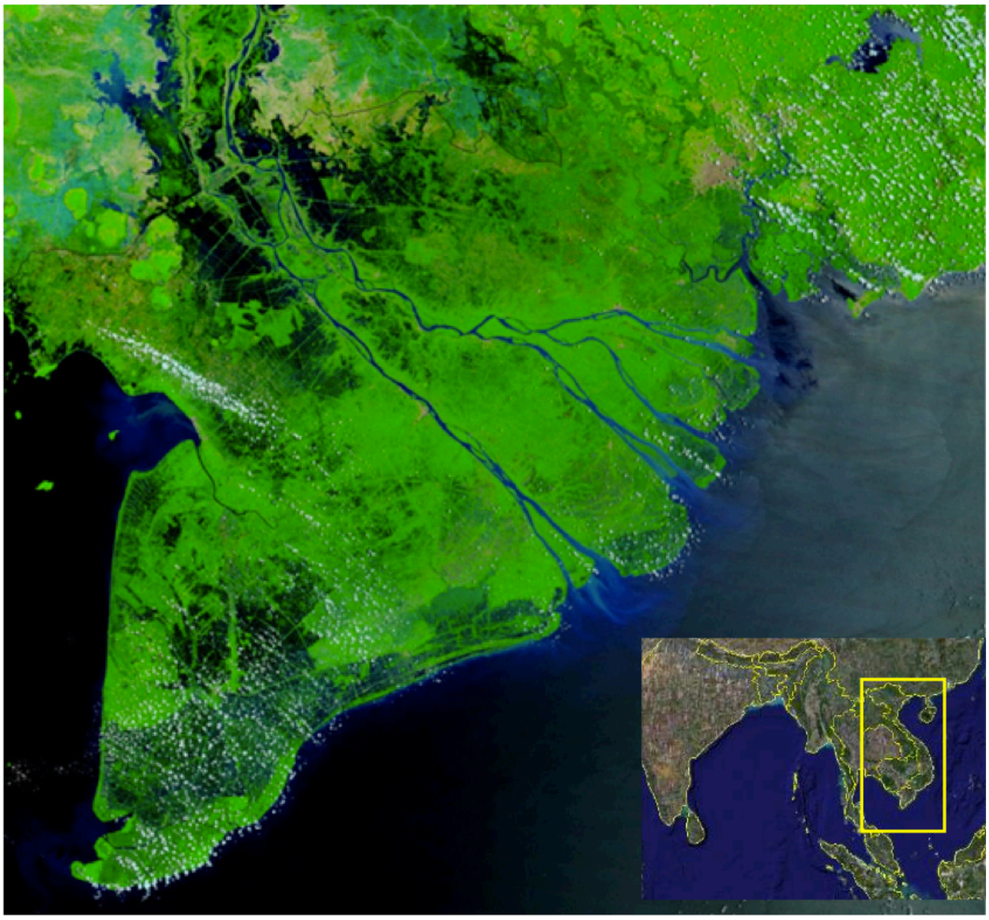
The GBM Delta is one of the world's largest (~100,000 km^2) and most dynamic deltas draining land from Bangladesh, Bhutan, China, India and Nepal. The delta covers most of Bangladesh and part of West Bengal, India, with many of the 147 million people (in 2000) living in the delta under extreme poverty 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.



II. The Mekong Delta

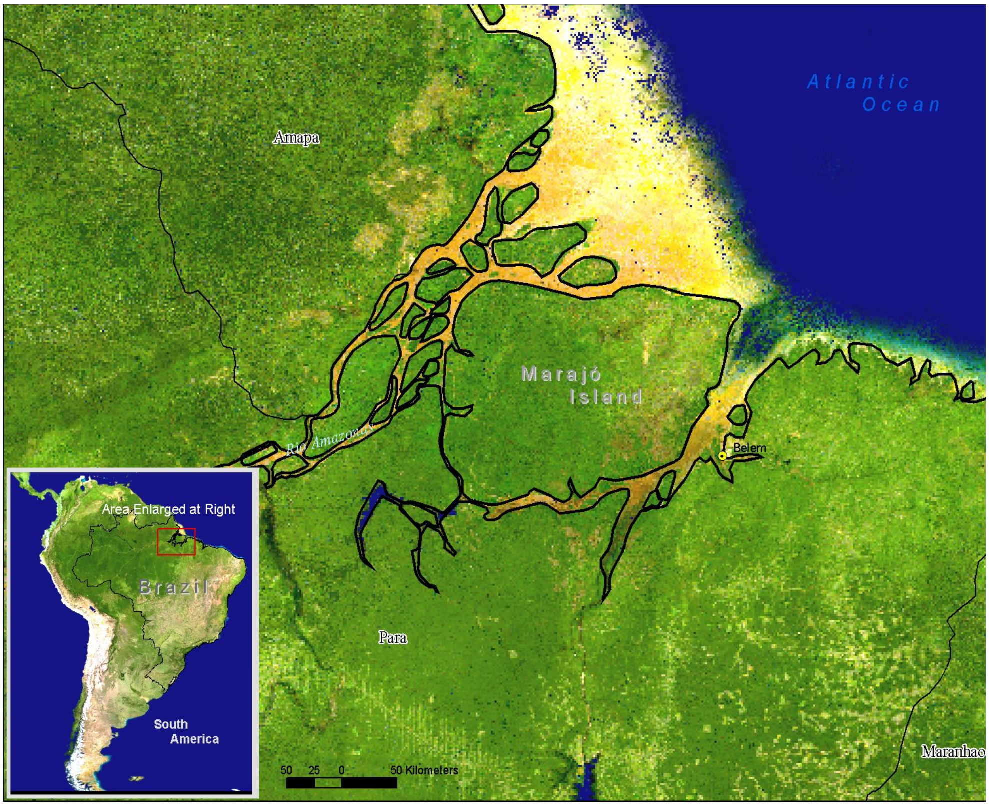
The Mekong Delta is considered as the world's third largest delta (with an area of 93,781 km^2 and population of 17 million), is one of Asia's main food baskets, and is second only to the Amazon in terms of fish biodiversity [*WWF*, 2008]. The major challenges in the MRD can be attributed to socio-economic 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].



III. 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, deforestion 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.


Atlantic
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UNIVERSITY OF MINNESOTA
Driven to Discover℠

Efi Foufoula–Georgiou's group

University of Minnesota

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

Research Themes and Accomplishments during 2014-2015

Our research efforts over the past year have concentrated on two main areas: (1) a new algorithm for improved satellite rainfall retrieval over snow-covered land surfaces and coastal zones and (2) delta channel network topology and dynamics for delta comparison, physical inference and vulnerability assessment. Application of the developed frameworks will be performed in the Mekong, Ganges, and Amazon river deltas, which are the focus of the DELTAS project funded under NSF Belmont Forum-G8 Collaborative Research. However, the developed frameworks are general and transferable to other deltas.

1. A new Algorithm for Improved Satellite Rainfall Retrieval over Snow-Covered Land Surfaces and Coastal Zones.

Accurate estimation of rainfall over coastal regions will improve our ability to understand the socio-ecological response of these vulnerable systems to extremes, improve flood forecasting and risk management practices. In these regions, ground measurements from rain gauges and ground radars are not readily available and satellites offer the only reliable source of data. The launch of the Tropical Rainfall Measuring Mission (TRMM) satellite set a benchmark for spaceborne estimation of rainfall over the tropics, providing an invaluable set of decadal rainfall observations with unprecedented accuracy and coverage. The recently launched Global Precipitation Measurement (GPM) core satellite, together with a constellation of partner satellites, will provide a considerably extended spatial coverage of precipitation over higher latitudes. However, improvements on the accuracy and space-time resolution of precipitation retrievals over complex land surfaces require the development of new methodologies.

For precipitation retrievals over land, using satellite measurements in microwave bands, it is important to properly discriminate the weak rainfall signals from strong and highly variable background surface emission. Traditionally, land rainfall retrieval methods often rely on a weak signal of rainfall scattering on high-frequency channels (85 GHz) and make use of empirical thresholding and regression-based techniques. Due to the increased ground surface signal interference, precipitation retrieval over radiometrically complex land surfaces—especially over snow-covered lands, deserts and coastal areas—is of particular challenge for this class of retrieval techniques.

To address this, we evaluated the results by the recently proposed Shrunken locally linear embedding Algorithm for Retrieval of Precipitation (ShARP), over a radiometrically complex terrain and coastal areas using the data provided by the TRMM satellite [*Ebtehaj et al.*, 2015]. We explore the idea of "implicitly" encoding the land surface information content across all available frequency channels. In essence, the a priori database in this Bayesian algorithm is properly organized in an algebraically tractable manner via two fat matrices, called "rainfall" and "spectral dictionaries". Spectral dictionary contains a large a priori collection of brightness temperature (BT) measurements, while the rainfall dictionary encompasses their corresponding simulated or observed rainfall profiles. Given a pixel-level measurement of spectral BT values, this algorithm relies on a nearest neighbor search that uses information content of all frequency channels to properly narrow down the retrieval problem to a few physically relevant spectral candidates and their rainfall profiles. In this step, our algorithm classifies the measured BT values into raining and non-raining signatures via a simple probabilistic voting rule (detection step). Then for the raining BT measurements, it exploits a modern regularized weighted least-squares estimator to retrieve the rainfall values of interest (estimation step).

To this end, the ShARP retrieval experiments are performed over a region in South and Southeast Asia, partly covering the Tibetan Highlands, Himalayas, Ganges-Brahmaputra-Meghna river basins and its delta. This region is unique in terms of its diverse land surface radiation regime and precipitation type within the TRMM field of view.

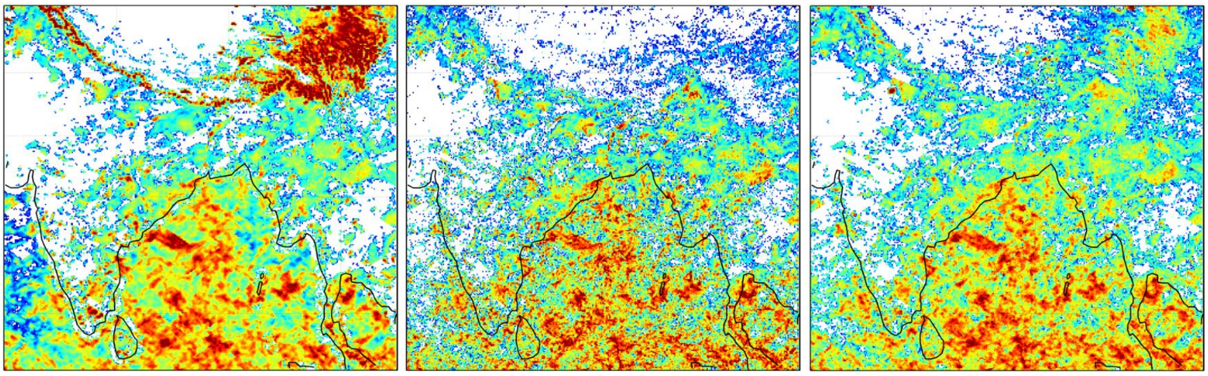

Figure 1. The three month rainfall [mm] retrievals--October-December of 2013--over the southwest Asia including the Tibetan Highlands and Ganges-Brahmaputra-Meghna river basin, shown at 0.1-degree. The standard TMI-2A12 (left panel), radar PR-2A25 (right panel) and ShARP retrievals. The results clearly indicate that ShARP can significantly mitigate the effects of background noise due to snow cover lands, which results in rainfall over estimation over the Himalayan range and headwaters of the Brahmaputra river basin. These results promise improved hydrologic analysis of mid-latitude and in cold climates.

We elucidate promising results by ShARP over snow covered land surfaces and at the vicinity of coastlines, in comparison with the land rainfall retrievals of the standard TRMM-2A12 product. Specifically, using the TRMM-2A25 radar product as a reference, we provide evidence that the ShARP algorithm can significantly reduce the rainfall over estimation due to the background snow contamination and markedly improve detection and retrieval of rainfall at the vicinity of coastlines (see Figure 1). During the calendar year 2013, we demonstrate that over the study domain the root mean squared difference can be reduced up to 38% annually, while the reduction can reach up to 70% during the cold months.

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

River deltas are intricate landscapes with complex channel networks that self-organize to deliver water, sediment, and nutrients from the apex to the delta top and eventually to the coastal zone. The natural balance of material and energy fluxes, which maintains a stable hydrologic, geomorphologic, and ecological state of a river delta, is often disrupted by external perturbations causing topological and dynamical changes in the delta structure and function. A formal quantitative framework for studying delta channel network connectivity and transport dynamics and their response to change is lacking.

We have introduced a graph theoretic approach for studying delta channel networks, where deltaic systems are represented by rooted directed acyclic graphs. Using spectral graph theory we developed methods for extracting sub-networks from apex to the shoreline, upstream and downstream subnetworks, and for computing steady flux propagation in the network. The latter allowed us to construct vulnerability maps that quantify the relative change of sediment and water delivery to the shoreline outlets in response to possible perturbations in hundreds of upstream links [*Tejedor et al.*, 2015a]. We also developed metrics that capture unique physical, topological, and dynamical aspects of delta networks with the ultimate objective that deltas projected in such a "metric space" can be compared and contrasted and also analyzed for relative vulnerability (or resilience) to change. The framework was applied to seven major deltas and its potential for delta classification and comparison was demonstrated [*Tejedor et al.*, 2015b].

A river delta, characterized by its channel network, is represented by a directed graph, i.e., a collection of vertices (bifurcations and junctions in the delta) and directed edges (channels in-between vertices, where the direction is given by the flow). All information about the network connectivity can be stored in a sparse adjacency matrix that allows us to extract important network topologic information by straightforward algebraic manipulations (Figure 1).

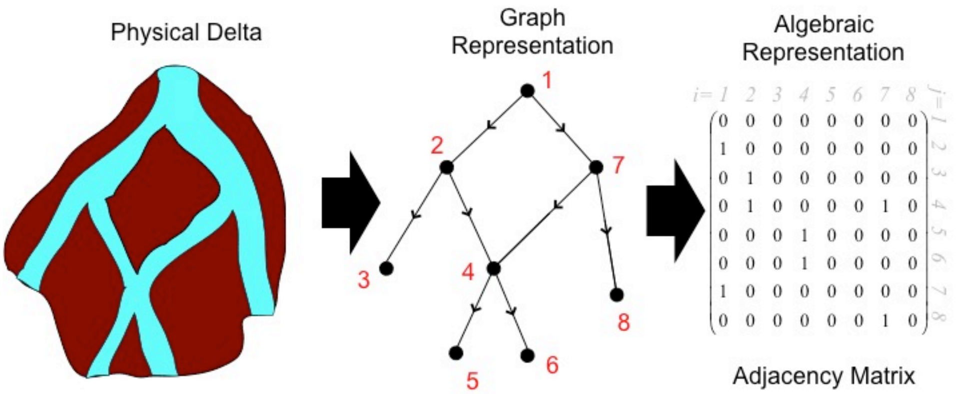

Figure 1. Quantitative framework for studying delta channel network connectivity based on spectral graph theory.

We used this framework to introduce a suite of graph-theoretic and entropy-based metrics, to quantify two components of a delta's complexity: (1) *Topologic,* imposed by the network connectivity and (2) *Dynamic,* dictated by the flux partitioning and distribution. The metrics are aimed to facilitate comparing, contrasting, and establishing connections between deltaic structure, process, and form.

We illustrate the proposed analysis using seven deltas in diverse morphodynamic environments and of various degrees of channel complexity (see Figure 2 left panel). We project deltas into a topo-dynamic space whose coordinates are given by the topologic and dynamic delta complexity metrics, and show that this space provides a basis for delta comparison and physical insight into their dynamic behavior (Figure 2 right panel). Jointly, the topologic and dynamic complexity of a rive delta places it in a unique position in the delta topo-dynamic space, revealing that as topologic complexity decreases (e.g., fewer loops and simpler subnetwork structures connecting the apex to the shoreline outlets) the dynamic complexity (flux exchanged among subnetworks) increases. At the limit of minimum (maximum) topologic (dynamic) complexity is a purely bifurcating tree and we see that the simpler and younger deltas (e.g., Wax Lake and Mossy) are, in fact, closer to such a bifurcating tree in the topo-dynamic space. This is also observed in all other metrics.

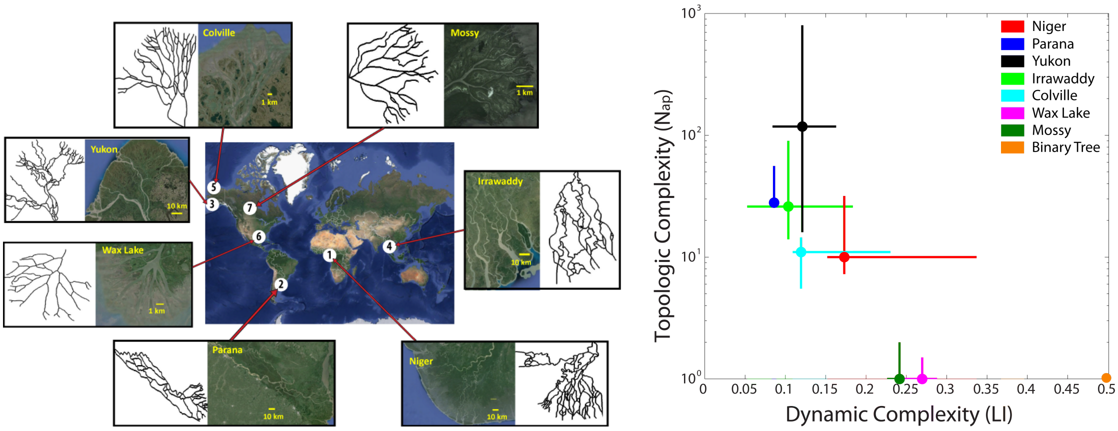

Figure 2. (left) Location of seven deltas and their corresponding channel networks numbered according to size (largest to smallest area). We used the Smart and Moruzzi [1971] networks for (1) Niger, (2) Parana, (3) Yukon, (4) Irrawaddy, and (5) Colville Deltas. For (6) Wax Lake we used the network extracted by Edmonds et al. [2011]. We have extracted the network of (7) Mossy from Google Earth. Satellite images are copyrighted by Digital Globe Inc. 2014. (right) Topo-dynamic complexity space for deltas. The x-axis corresponds to the dynamic exchange of the different subnetworks measured by the Leakage Index (*LI*), and the y-axis corresponds to the topologic complexity measured by the Number of alternative paths from apex to outlet (N_{ap}). Each colored cross corresponds to a different delta, and the orange dot corresponds to a binary tree. The vertical (horizontal) component of each cross runs from the 25th until the 75th percentile of the Number of alternative paths (Leakage Index).

We also show that the examined metrics relate to the intuitive notion of vulnerability, measured by the impact of upstream flux changes to the shoreline flux (Figure 3). The topologic and dynamic complexity of deltas seem to relate to its vulnerability to change, i.e., to the way a delta responds in propagating upstream disturbances to its shoreline outlets. Specifically, we report an inverse non-trivial relationship between vulnerability and two indices of topologic (Number of alternative paths) and dynamic (Conditional Entropy) metrics.

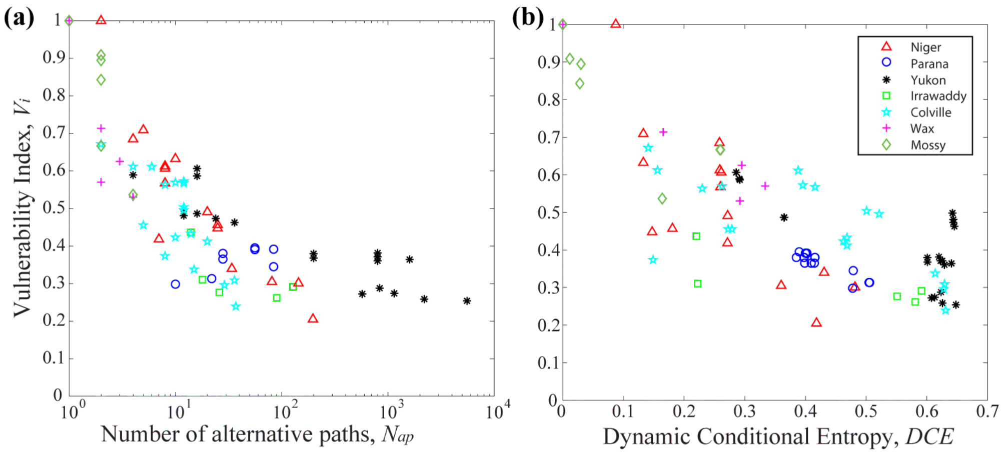

Figure 3. Relation of Vulnerability to Topologic and Dynamic Complexity. Vulnerability Index vs. Number of alternative paths (left) and vs. Dynamic Conditional Entropy (right). As expected, the more complex a delta is the more "robust" it is to change. This is because alternative paths and equitable flux distribution minimize the effects of a flux change in upstream links to the flux reaching the outlet.

Finally, a spatially-explicit interrogation of a delta in terms of its normalized number of links versus normalized distance from the apex (*delta width function*) reveals that one can quantify easily deltas that are mostly divergent, convergent or geologically confined, as well as transitions from one regime to another (Figure 4a).

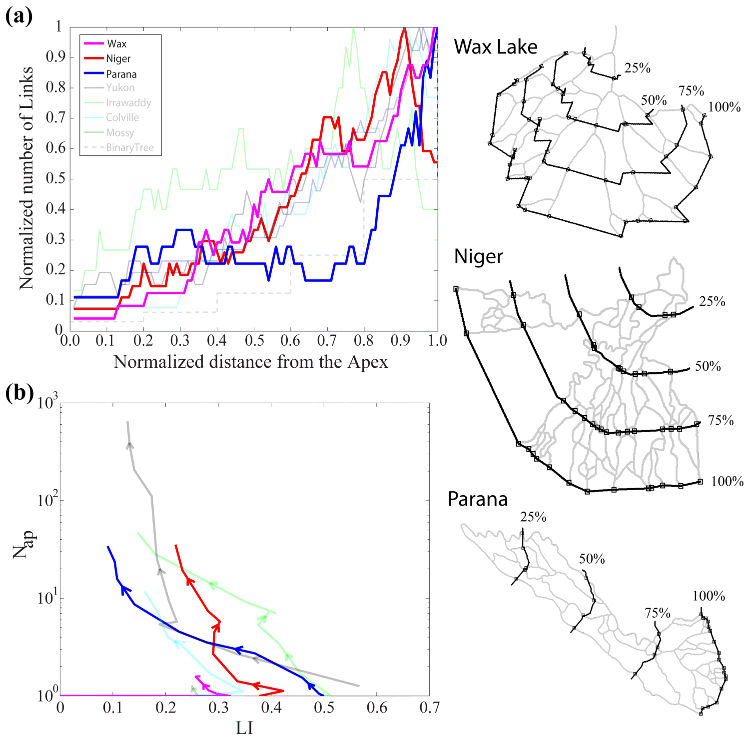

Figure 4. Spatially explicit metrics of complexity. (Right panels) Schematic representation of contours radially scaled at normalized distances of 25%, 50%, 75% and 100% of the current shoreline. The squares show the intersections at the different distances. (a) *Delta width function* for the seven deltas examined. (b) Each line represents the smoothened trajectory in the topo-dynamic complexity space (intersection of the mean of both Leakage Index and Number of alternative paths) for each radially scaled delta from the apex to the shoreline. Note, that if actual data on shoreline and channel network evolution existed this plot would capture the progression of the topo-dynamic complexity of the evolving delta.

We observe that for tree-like deltas (Wax Lake and Mossy), the normalized number of links is an increasing function of the normalized distance achieving the maximum at the current shoreline similar to the behavior for the binary tree. More complex deltas, on the other hand, attain a maximum before the current shoreline (e.g., Irrawaddy at normalized distance ≈ 0.78, Colville and Niger ≈ 0.90, and Yukon ≈ 0.95) except for Parana with maximum located at the current shoreline. These results highlight the idea that Parana can be thought of as two deltas in tandem [*Smart and Moruzzi,* 1971]: the upper half near the apex with a narrow region similar to braided rivers containing the core links, and the lower half with a topology similar to a bifurcation-dominated delta. Although the spatial analysis of a mature delta cannot be used as a surrogate for its temporal evolution (due to the possibility of internal rearrangement of channels caused by avulsions and major flooding) it can still be used as a rough proxy. Figure 4b shows the evolution of the seven deltas in the topo-dynamic space. The arrows indicate the direction of increasing distance from the apex. Each line corresponds to the mean topologic complexity and to the mean dynamic complexity as we move from the apex to the shoreline. From a spatial evolution perspective, deltas evolve by increasing their topologic complexity (in terms of N_{ap}) and decreasing their dynamic complexity (in terms of LI). This is compatible with the idea that young (old) deltas are topologically simple (complex) with subnetworks exchanging a large (small) proportion of fluxes.

Future Research (2015–2016)

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

1. A new Algorithm for Improved Satellite Rainfall Retrieval over Snow-Covered Land Surfaces and Coastal Zones

1. We will identify all the TRMM overpasses over Ganges, Mekong, and Amazon for a five-year period (initially and longer periods later) and obtain the TMI (passive sensor) and PR (active sensor) data from NASA's TRMM web site.
2. We will apply the developed methodology of rainfall retrieval, using TRMM passive microwave and coincidental PR radar, over the Ganges, Mekong, and Amazon deltas for several extreme storms and compare these retrievals to the current NASA products (2A-12).
3. We will collaborate with the team of Prof. Steve Goodbred at Vanderbilt University (partner of the BF-DELTAS project) to obtain rain gauge data in the Ganges for validation of the retrieval algorithm.
4. We will collaborate with the team at CUNY and the German Remote Sensing Data Center (partners of the Belmont Forum project) to develop delta inundation maps and incorporate this information into precipitation retrievals.

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

1. We will acquire SRTM topography data and extract the channel network for the Amazon River Delta. For Year 2, we have extracted manually the channel network for the Mekong Delta and did some preliminary analysis.
2. We will populate the topo-dynamic space with more deltas and advance the idea of using these metrics for delta classification.
3. We will analyze delta channel network evolution using historical data to quantify how delta complexity changes over time, e.g., according to the processes involved such as avulsions versus channel growth. The first case study will be the Wax Lake delta for which channel networks of the delta are available and the delta is simple enough to extract the networks manually. Extension to other deltas will be performed in Year 3.
4. 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?
5. We will analyze simulated deltas using Delft 3D or RCMs under varying sets of physical parameters and compare the topo-dynamic space of simulated deltas to the space of real deltas (the seven deltas already analyzed and some new ones) to gain insight into process and form.
6. We will extend the analysis to "networks upon networks" (beyond channels) to model surface to sub-surface flux exchange, nutrient transport, and ecological processes on deltas using graph theoretic approaches.

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Tejedor, A., A. Longjas, I. Zaliapin, and E. Foufoula-Georgiou (2015), "A graph-theoretic approach to River Deltas: Studying complexity, universality, and vulnerability to change", EGU General Assembly, Vienna, Austria, 12-17 April.

Tejedor, A., A. Longjas, I. Zaliapin, and E. Foufoula-Georgiou (2015), "A graph-theoretic approach to Studying Deltaic Systems: Quantifying Complexity and Self-Organization", CSDMS Annual Meeting, Boulder, Colorado, 26-29 May.

Tejedor, A., A. Longjas, I. Zaliapin, J. Syvitski, and E. Foufoula-Georgiou (2015), "Complexity and Robustness of Deltaic systems: A graph-theoretic approach", INQUA, Japan.

Tessler, Z., C. Vörösmarty, E. Foufoula-Georgiou, and M. Ebtehaj (2014), Spatial and temporal patterns of rainfall and inundation in the Amazon, Ganges, and Mekong deltas, Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September.

Zanardo, S., A. Hilberts, E. Foufoula-Georgiou, and W. Dietrich (2014), Emergent phase shift between diurnal transpiration maxima and stream flow minima during base flow as diagnostic of eco-hydrologic interactions in landscapes, EGU General Assembly, Vienna, Austria, 27 April – 2 May.

Irina Overeem and Stephanie Higgins

Community Surface Dynamics Modeling System

Research Themes and Accomplishments during 2014-2015

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. We have begun construction of this tool on top of the CSDMS open-source modeling framework, developed under separate NSF funding. CSDMS's Web-based Modeling Tool, called WMT, 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. 1). Under Belmont Forum funding in Year 2, we have developed service components for Delta-RADS that facilitate delta risk modeling. These service components, described below, will shortly be incorporated into WMT and released as Delta-RADS after testing.

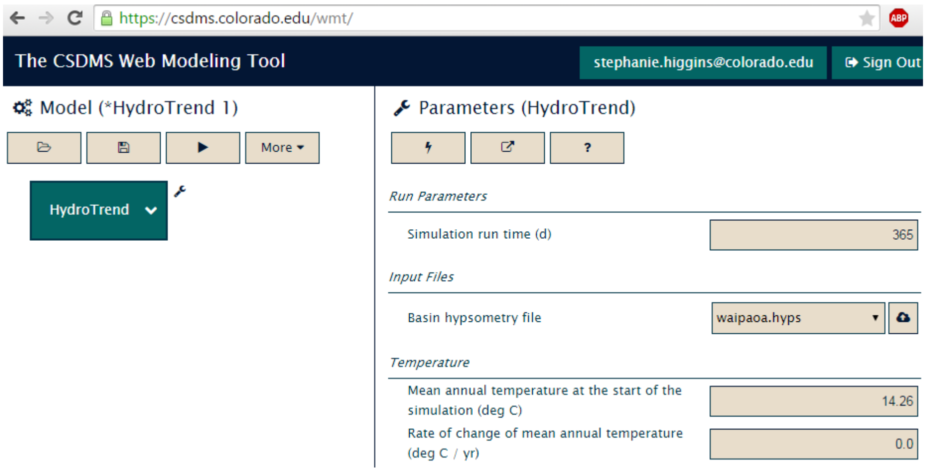

Figure 1. The Web Modeling Tool at csdms.colorado.edu, which allows users to submit modeling tasks to the supercomputer Beach and download output through the web.

1. GIS delta data for model simulations

Delta-RADS aims to include a GIS modeling system to support quantitative mapping and definition of functional relationships of the bio-physical environment of deltas as well as their social and economic dynamics. Towards that end, we have developed tools to generate GeoTIFFs and shapefiles of relevant datasets for delta modeling, which users can download to use in other studies or convert into model input file formats for simulations in Delta-RADS. Fig. 2 shows an example of drainage basins in Southeast Asia defined with a new service component. Using this tool, the user specifies the latitude and longitude of a point of interest along a river (e.g., the brown and black circles in Fig. 2, which correspond to gauging stations on the Ganges and Brahmaputra rivers, respectively). 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. These watershed boundaries then can be overlayed with global map datasets e.g. population density or GDP and these data can then be clipped appropriately. The next tool generates hypsometry input files for HydroTrend v. 3.0 [*Kettner & Syvitski, 2008*] from the delineated DEM, and with that model allow first-order simulations of sediment inputs to deltas under a variety of conditions (e.g., with and without dams, or with multiple climatological sub-basins) (Fig. 3). The fully open-source Geospatial Data Abstraction Library (GDAL) has also been wrapped in order to allow users to cut any raster dataset, such as population, soil, land use, or species distribution maps needed for model input. These tools are undergoing final testing for compatibility with different dataset projections, after which they will be incorporated into WMT.

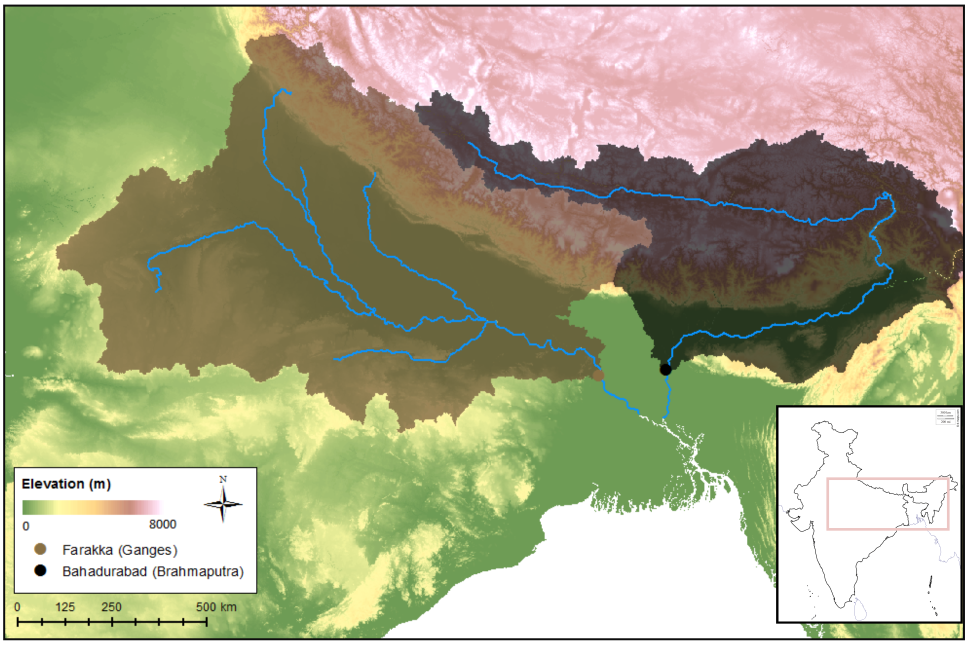

Figure 2. Ganges (brown) and Brahmaputra (grey) watersheds above the rivers' convergence point at the apex of the Ganges-Brahmaputra-Meghna delta, defined with the new service component.

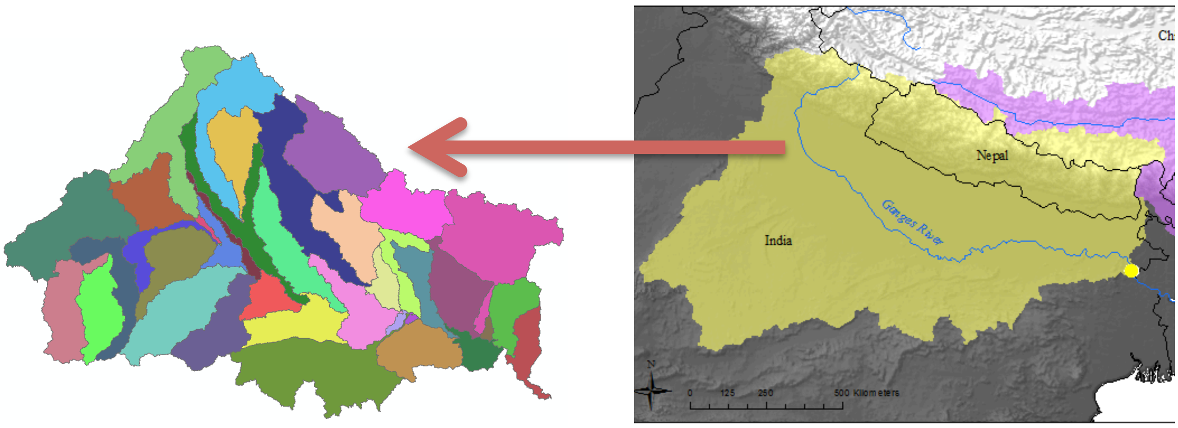

Figure 3. The automatic generation of input files simplifies the application of HydroTrend to multiple sub-basins, improving modeling of large basins. Data on Ganges sub-basins: *Pervez & Henebry (2014)*.

2. Ganges-Brahmaputra delta study using the new service components

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 have used the core service components of the Delta-RADS tool (above) to begin an investigation of the impacts of e.g. future climate change, future irrigation and damming on sediment transport to the Ganges-Brahmaputra Meghna delta (GBM). This investigation is both an important case study and a test of new Delta-RADS components.

We have analyzed meteorological stations throughout the Ganges-Brahmaputra river drainage basin and collaborate with the USGS on the ingestion of regionally downscaled Global Climate Model data [*Pervez and Hennebry, 2014*] into the HydroTrend Model. Initial results show an increase in precipitation (~12% by 2100) with a small response in the sedimentary transport system, provided the erosional regimes remains relatively stable.

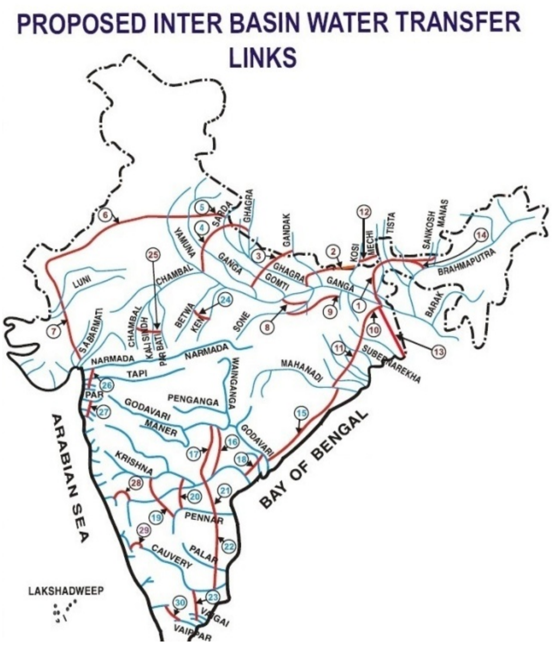

Figure 4. Summary of major rivers (blue) and potential link canals (red) in the IRI project. From the National Water Development Agency (NWDA), www.nwda.gov.in.

We examine the Indian Rivers Interlink (IRI), which aims to link several of India's major rivers via a network of reservoirs and canals (Fig. 4). Construction on the first three canals (#s 24, 26 and 27) has controversially begun. If the Interlink project moves forward, fourteen canals would ultimately divert water from tributaries of the Ganges and Brahmaputra rivers to drier areas in the south and west of India. This is expected to affect sediment transport to the Ganges-Brahmaputra Delta.

We are using WMT and the new Delta-RADS tools to model the impacts of the proposed diversions on using HydroTrend 3.0 [Kettner & Syvitski, 2008]. Preliminary results suggest that a single canal diverting water from Brahmaputra tributaries to the city of Kolkata could reduce sediment transport to the delta by up to 20% during peak flow [*Higgins et al., 2015*].

3. Involving stakeholders

A key principle of Delta-RADS is that it is to be developed via consultation with its intended users and stakeholders in order to ensure that it adequately addresses the realities of delta management. PI Overeem maintains a relationship with the Bangladesh Water Development Board, and communicates results of this study to a major WorldBank funded development project of the Bangladesh Coastal Zone (Coastal Embankment Improvement Project, CEIP-C3: Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone). This integrated WB project advocates for sustainable polder design and management. We presented the delta data and modeling framework considerations to stakeholders at the 'Deltas in Times of Climate Change II' Conference with stakeholder participants from deltas worldwide.

Through Belmont Forum DELTAS PI Ian Harrison, we have developed relationships with Rajeev Raghavan, the South Asia Regional Chair for International Union for Conservation of Nature (IUCN)'s Freshwater Fish Specialist Group and part of IUCN's Freshwater Conservation Subcommittee; Jorg Freyhof, Executive Director of the Group on Earth Observations - Biodiversity Observation Network (GEO BON), an international organization whose mission is to provide biodiversity information to policy makers; and Parineeta Dandekar from the South Asian Network for Dams, Rivers and People (DANDRP). We will further develop Delta-RADS with input from these collaborators regarding their science needs.

Additional Outreach 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.

Looking forward

In the next year, the CU Boulder team will:

- Continue to develop service components for Delta-RADS
- Test and formally release Delta-RADS through WMT
- Complete the study of sediment transport to the GBM affected by the Indian Rivers Interlink (IRI) project
- Complete the study of projected sediment transport to the GBM affected future climate change and monsoonal intensification.
- Produce a dataset of watershed changes (GeoTIFF files) of the IRI project, which will be hosted online to facilitate additional studies of the ecological and social impacts of IRI using these input files.
- PI Overeem with several Belmont Forum International team members, has proposed to convene a session at AGU 2015: "Sustainable Deltas: Multidisciplinary Analyses of Complex Systems"

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Papers

Chen, Y., Overeem, I., Kettner, A.J., Gao, S., Syvitski, J.P.M., (accepted. 2015). Modeling Flood Dynamics along the Super-elevated Channel Belt of the Yellow River over the Last 3,000 years. *Journal of Geophysical Research.*

Hutton, E., Piper, M., Overeem, I., Kettner, A.J., 2014. BUILDING SUSTAINABLE SOFTWARE - THE CSDMS APPROACH, Working towards Sustainable Software for Science: Practice and Experiences, *WSSSPE2*, November 16, 2014, New Orleans, USA.

Conference presentations and abstracts

Higgins, S., Overeem, I., and Syvitski, J. P. M. (2014), Monitoring subsidence with Interferometric Synthetic Aperture Radar (InSAR), *Annual Meeting of the American Geophysical Union (AGU),* 15-19 Dec 2015, San Francisco, CA, USA.

Higgins, S., Overeem, I., and Syvitski, J. P. M. (2015), Potential impacts of Indian Rivers Inter-links on sediment transport to the Ganges-Brahmaputra Delta, *Models Meet Data, Data Meet Models: Annual Meeting of the Community Surface Dynamics Modeling System (CSDMS),* 26-28 May 2015, Boulder, CO, USA.

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Charles Vörösmarty and Zachary Tessler

CUNY Environmental CrossRoads Initiative

City College of New York

Research Themes and Accomplishments during 2014-2015

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: Precipitation and surface inundation patterns in space and time with respect to underlying land-cover and land-use.

1. Environmental Stress and Vulnerability analysis.

In an expansion of efforts from Year 1 of the project, 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 the community.

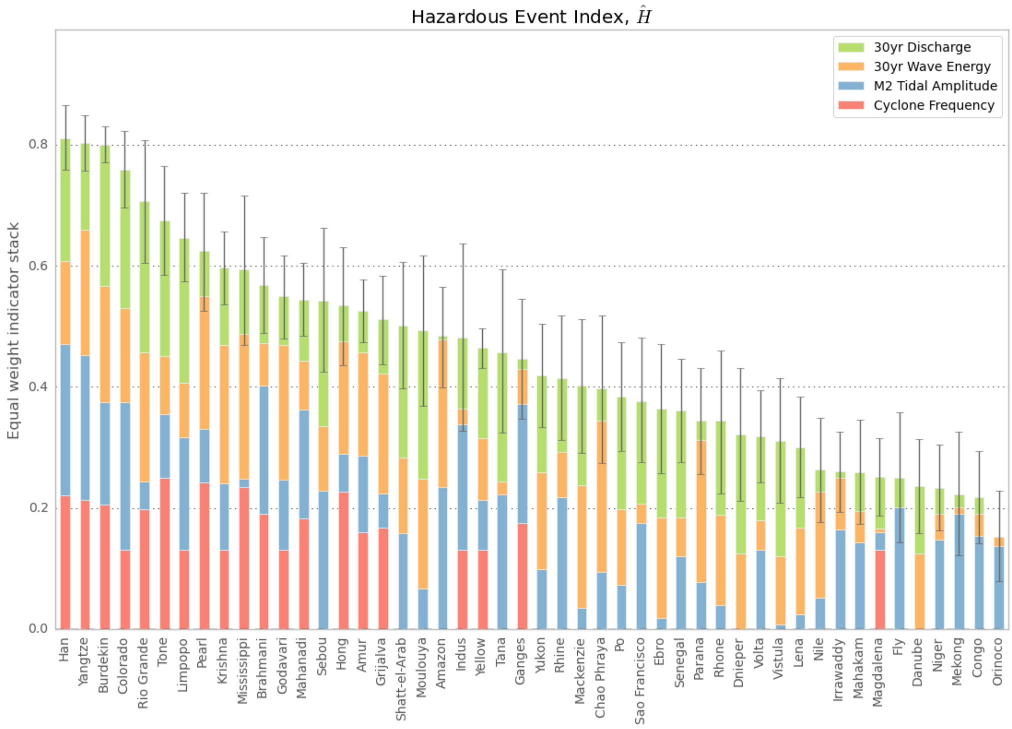

Figure 1. Hazardous Event Index

We have developed a theoretical model for the change in coastal risk resulting from Relative Sea Level Rise induced by environmental changes in the upstream, coastal, and offshore domains. Since the environmental index, termed the Anthropogenic Conditioning Index, developed in the previous year 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 developed 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 can 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.

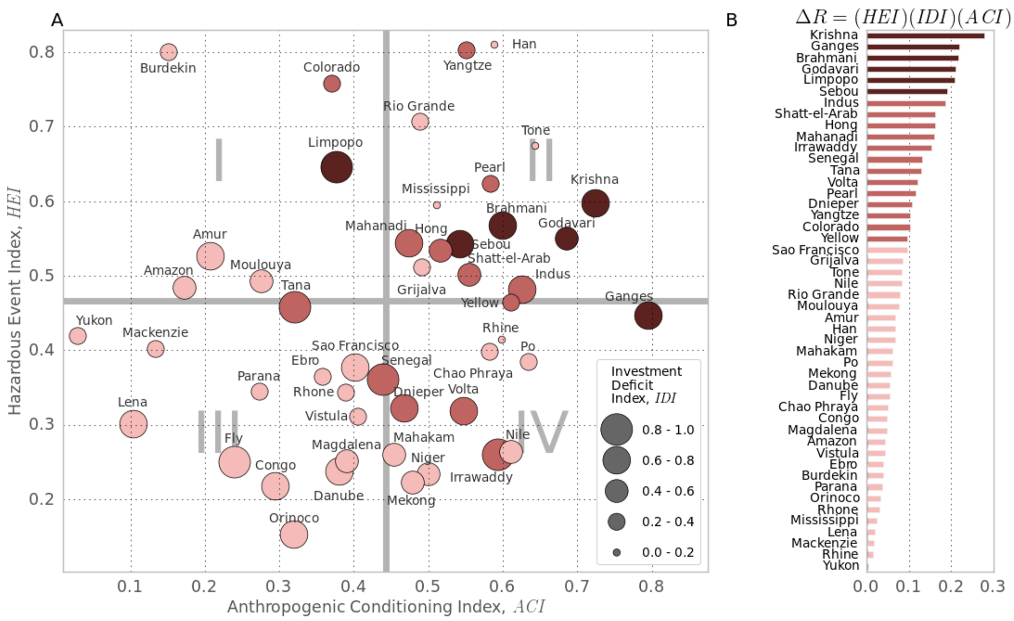

Figure 2. Delta risk space. HEI is the Hazardous Events Index, IDI is the Investment Deficit Index, and ACI is the Anthropogenic Conditioning Index.

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).

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.

This work has been accepted in *Science*:

Tessler, Z.D., C.J. Vorosmarty, M. Grossberg, I. Gladkova, H. Aizenman, J. Syvitski, and E. Foufoula-Georgiou, Profiling risk and sustainability in coastal deltas of the world, *Science*, 349 (6248), 638-643, DOI: 10.1126/science.aab3574.

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.

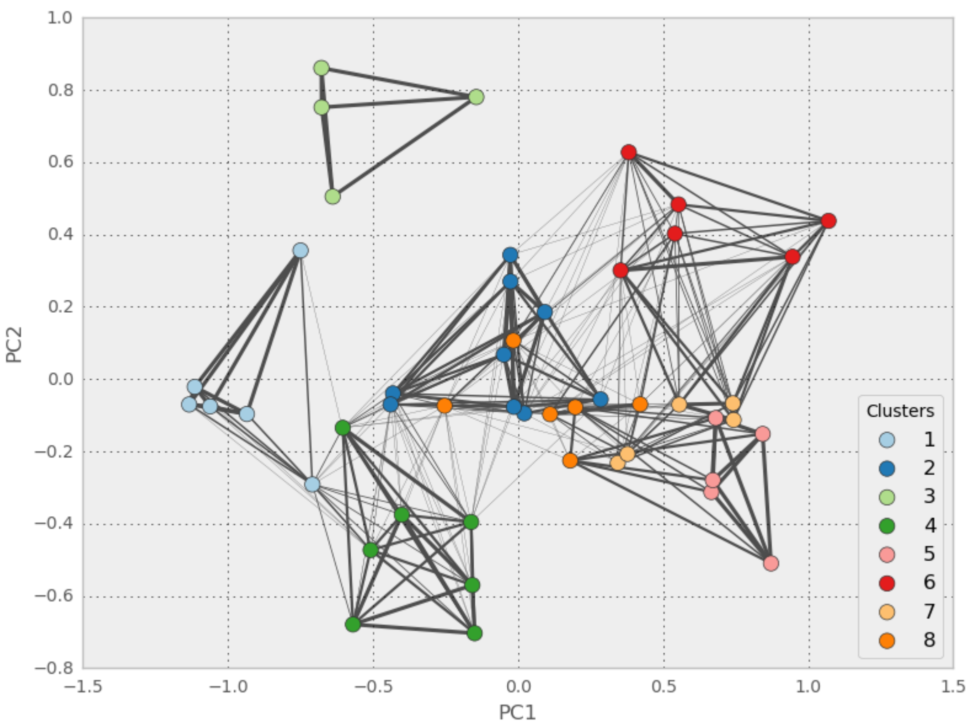

Figure 3. Global delta clusters, projected into the first two PCA components. Colors indicate KM8 cluster for a given delta, and line weight indicates the number of alternate cluster algorithms that assign two nodes to the same cluster.

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 3).

The Amazon is in Cluster 1 (Figure 3, 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 3, 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.

This work has been submitted to *Sustainability Science*, and is currently in review.

3. Precipitation and surface inundation patterns

In the first project year, we began work to identify spatial and temporal patterns of wetland inundation in the three case study deltas. Regular delta flooding supports sediment dispersal processes and is important for the healthy functioning of many natural ecosystems. At the same time, flooding in populated areas can be catastrophic to communities and infrastructure. This research investigates spatial and temporal surface inundation response to local rainfall patterns and major precipitation events over the Amazon, Ganges-Brahmaputra, and Mekong deltas. Inferred inundation sensitivity maps are compared with land-cover and land-use patterns within and across the three deltas.

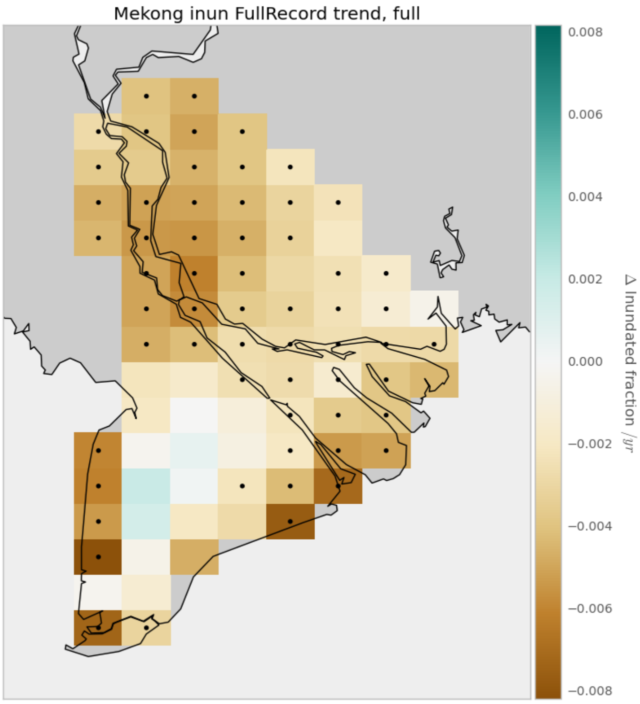

Figure 4. Inundation trends in the Mekong over the 1992-2013 time period. Dots indicate statistical significance.

We are utilizing a new active and passive microwave-based global time-series, SWAMPS (Surface Water Microwave Product Series). Last year, we began by conducting a spatial analysis of dominant inundation modes for the Amazon, Ganges, and Mekong deltas using Empirical Orthogonal Function analysis (Principal Component Analysis). This year, we are working to compare observed inundation patterns with several hydrological drivers: local precipitation from the Tropical Rainfall Measuring Mission, river discharge from the upstream watershed simulated by WBMplus, and offshore wave energy from WAVEWATCH III as an indicator of storm surge.

Early analysis of results in the Mekong suggest a small but statistically significant drying trend (Figure 4) over the 1992-2013 timespan of the SWAMPS inundation data. Drying is significant in the upper delta and close to the main river distributary channels. Predominately irrigation-driven portions of the lower delta do not exhibit these trends.

Seasonality analysis suggests that the drying trend in the upper delta is predominately due to drier conditions in the Autumn and Winter, coastal trends are dominated by reduced inundation in the Summer, while the lower irrigation driven areas are getting wetter particularly in the Spring, and also in the Autumn. Initial results show a reduction in rainfall over the entire delta during this period, but this does not explain the observed spatial patterns. Changes to irrigation practices are a possible explanation, and this is currently being explored.

Future Research 2015-2016

1. IN PROGRESS: Examine seasonality of changes in inundation, precipitation, river discharge, and coastal wave energy to determine dominant drivers of change in the three case study deltas
2. IN PROGRESS: Spatial correlation and decorrelation timescale analysis between precipitation over a grid cell and change in inundation
3. Augmentation of inundation with high-resolution SAR snapshot imagery. We currently have several triplets of 5-day repeat scenes over the Mekong, Ganges, and Amazon deltas.
4. Comparison of spatial and temporal patterns of rainfall-driven inundation with land-use and land-cover information, with the goal of developing spatially-explicit inundation vulnerability maps.

Publications and Presentations

Tessler, Z.D., C.J. Vörösmarty, M. Grossberg, I. Gladkova, H. Aizenman, J. Syvitski, E. Foufoula-Georgiou. Profiling Risk and Sustainability in Coastal Deltas of the World. *Science*, in revision.

Tessler, Z.D., C.J. Vörösmarty, M. Grossberg, I. Gladkova, H. Aizenman. A global empirical typology of environmental change in deltas: anthropogenic drivers and implications for sustainable management. *Sustainability Science*, in review.

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Workshops and Conference Sessions

Impacts of Global Change on Deltas and Coastal Wetland Ecosystems: Scientific Advances in Support of Socioeconomic Resilience. Co-conveners: Zachary Tessler, Wenhong Li, Yoshiki Saito, Ge Sun. Session GC21D, AGU Fall Meeting, San Francisco, CA, 15-19 December 2014.

Science-to-Action: Aligning science with stakeholder and community needs in the Mekong Delta system. Chair: C.J. Vörösmarty. Organizer: Z.D. Tessler. Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September.

Steven Goodbred and Carol Wilson

Vanderbilt University

With contributions from Chris Small, Ryan Sincavage, Jennifer Pickering, Rip Hale, Chelsea Peters

Research Themes and Accomplishments during 2014-2015

Research in Year 2 on the BF-Deltas project has centered on identifying the key issues and regions associated with vulnerability and change in the Ganges-Brahmaputra River (G-B) delta, Bangladesh. The tectonically active G-B delta, with 150 million people and a vast, low-lying coastal plain, is potentially at great risk due to *i)* increased flooding and submergence under sea-level rise scenarios, *ii)* earthquakes and river avulsions due to tectonic deformation, and *iii)* decreased sediment loads due to damming/water redistribution in the drainage basin. Although these risks are widely recognized, our scientific understanding of the local conditions and processes within this, and other, complex deltaic landscapes is incomplete yet essential to effective and realistic management of these regions. We direct our focus on the dispersal of sediment within the G-B delta (both on modern and geologic timescales) and geomorphic changes occurring both naturally and anthropogenically. This information contributes to the modeling efforts and risk assessments being conducted by the larger DELTAS research community funded under NSF Belmont Forum-G8 Collaborative Research.

1. Bedload extraction within the G-B River delta—co-location with topography and the backwater

The Brahmaputra River occupied the tectonically active Sylhet Basin in eastern Bangladesh three times during the Holocene. Using samples from more than 200 closely-spaced (3-5 km) boreholes, we found sedimentary facies within Sylhet Basin can be characterized as stacked braidbelt sands in the proximal portion of the system (close to the G-B delta apex), with isolated sand lenses further downstream, indicating a transition from a highly mobile braidbelt to a less mobile distributary system. The majority of bed load is extracted within a distance of ~150 km from the delta apex, approximately coincident with the regional backwater reach of the Bengal Basin (Fig. 1), suggesting a link between the hydraulic and “morphodynamic” backwater reaches of the system. Downstream fining is more rapid in sediments associated with the long-term occupation of Sylhet Basin, for which sediment is trapped over a relatively short distance within the sand wedge of central Sylhet Basin, than those from the early- and late-Holocene occupations, for which sediment is distributed over a longer path that follows the course of the Old Brahmaputra River (Fig. 1). Fine-grained sediments preserved in the system do not display measureable downstream fining. The increased rate of sediment extraction in the eastern part of the basin is likely coupled with a subsidence maximum (~7 mm/year) associated with the foredeep of the Dauki thrust fault.

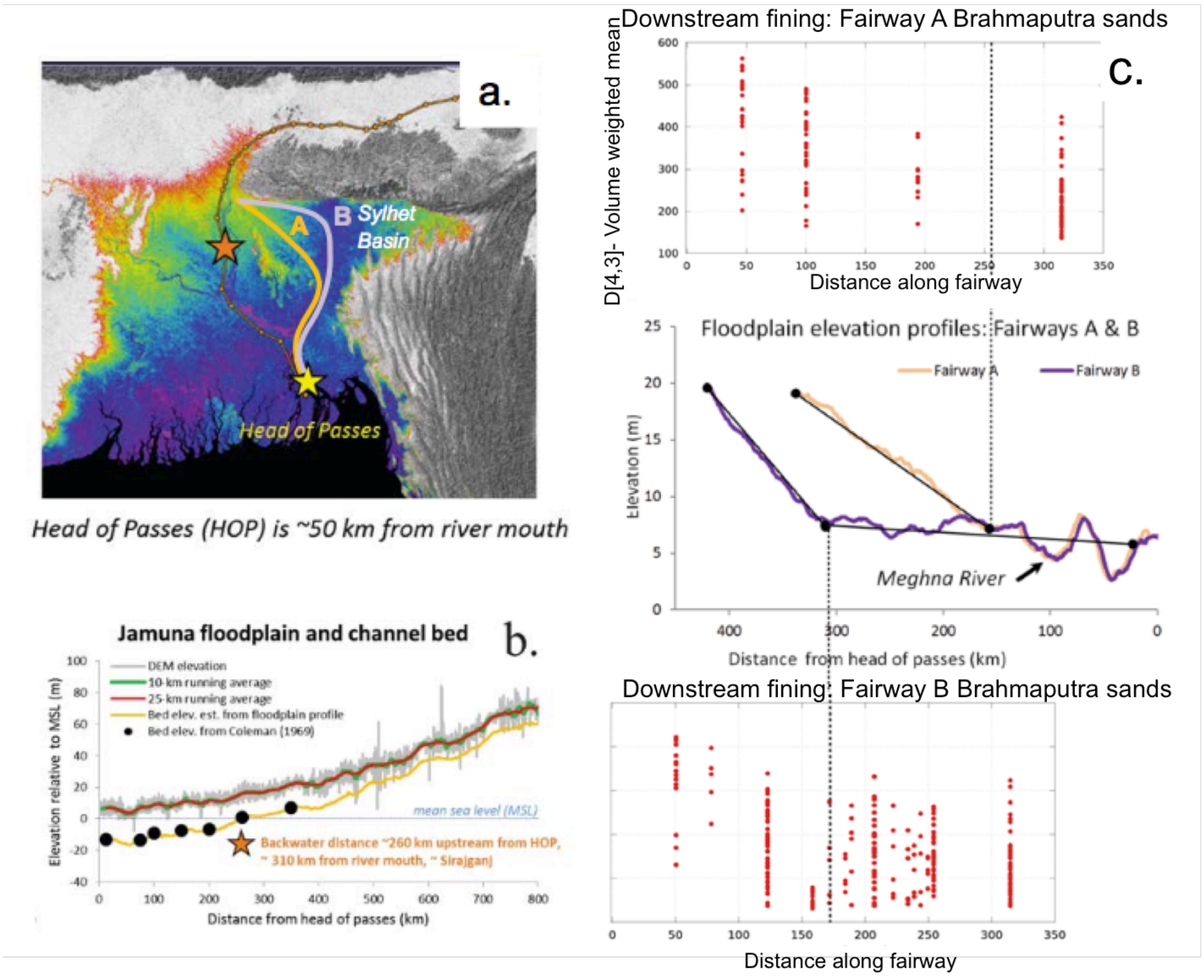
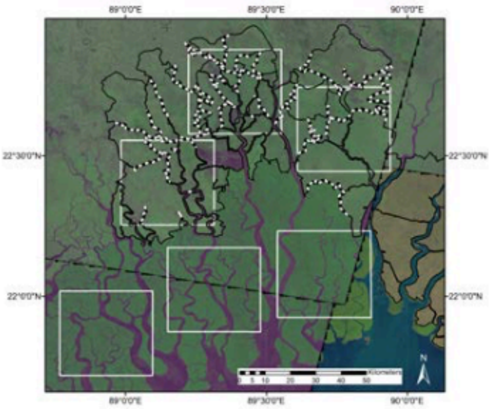
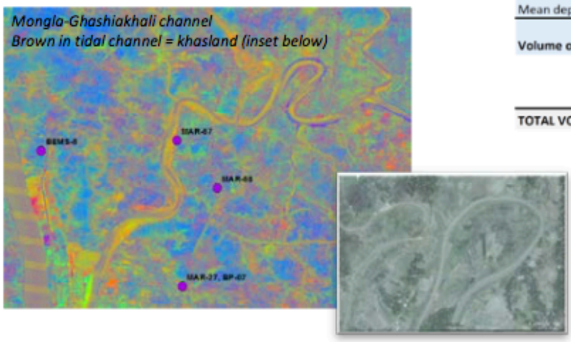


Figure 1. Elevation profiles along river pathways were calculated using DEM data. In Sylhet Basin, the majority of bed load (grain size >400 microns) is extracted within a distance of ~150 km from the delta apex, which roughly corresponds to the topographic break in slope (dotted line in c) and the regional backwater reach of the Bengal Basin (orange star in a & b).

2. Natural and Human-Induced Changes in G-B Tidal Channel Network

Unlike many lower-energy delta systems, the "abandoned" GB delta plain has remained relatively stable since being "abandoned" by avulsion of the main river mouths to the east several thousand years ago. Despite being cut off from its principal fluvial sediment supply, this region has continued to accrete sediments in the face of relative sea level rise. The immense sediment load discharge to the coast and its effective redistribution by the high-energy tides thus become mechanisms by which the GB delta can maintain large areas of coastal plain that are not directly influenced by the river discharge. In a completely natural system, the tidal channel network should evolve to a dynamic equilibrium with the tidal prism and sediment transport load. However, allogenic perturbations of (a) the channel network, (b) the tidal prism, or (c) sediment loading can force the system to adjust to a new steady-state regime through channel erosion, sedimentation, and water routing. A year ago, we started an analysis of historical Landsat imagery that showed a decrease in drainage density of the intertidal platforms of southwest Bangladesh due to the widespread construction of embanked islands (polders), mostly through the closure/restriction of primary creeks. Many infilling channels were also observed, where much of this new land is cultivated for shrimp production (locally termed 'khasland'). In contrast, results showed the tidal channel network in the Sundarbans forest is relatively stable by comparison. The impacts of reduced connectivity of the tidal channel network in embanked areas and their associated hydrodynamics were the focus of this year's analyses. Construction of the original embankments removed >1000 km of primary tidal creeks that formerly flooded and drained intertidal mangrove platforms (Fig 2). In addition, >90 km^2 of land has been reclaimed outside of polders through the closure of formerly active conduit channels (decrease in mean channel width from 256±91 m to 25±10 m; Fig 2). Field validation confirm tidal restriction by large sluice gates is prevalent, favoring local channel siltation (decrease in mean depth from 8-10 m to 2-3 m; accretion rates ~20 cm/yr). We document that with polderization, impoundment of primary creeks, and closure of 30-60% of conduit channels in the study area, an estimated $1.420 \cdot 10^6$ m^3 of water has been removed from the tidal prism and $12.3 \cdot 10^6$ MT of sediment annually infills khasland channels (~12% of the total annual sediment load supplied to the tidal delta plain [Rogers et al., 2013]; Fig 2). Further, severing the intertidal platform and large conduit channels from the tidal network appears to have accelerated lateral migration and straightening of remaining channels (Fig 3), which is the focus of current and future hydrodynamic survey work.





STUDY AREA SW BANGLADESH		
Poldered area in three study areas (m2) ~3500 km2	3.50E+09	
Mean inundation depth of intertidal platform at spring high water (m), from Auerbach et al, 2015	0.2	
Volume of water that flooded intertidal platform removed from the tidal prism due to polderization (m3)	**7.00E+08**	700 x 10^6 m^3
Mean width of tidal channels obstructed by polders [1° creeks] (m) (40-90m, 2-3 pixels on Landsat imagery)	50	
Length of tidal channels obstructed by polders [1° creeks] (m) (1021 km)	1021000	
Area of tidal channels obstructed by polders [1° creeks] (m2)	51050000	
Mean depth of primary creeks (m) (5-8 m bathymetry)	5	
Volume of water accommodated in primary creeks prior to embanking, (m3)	**2.55E+08**	255 x 10^6 m^3
Mean width removed from conduit channels due to khasland (m) , 251m-25m	226	
Length of tidal channels outside of polders with >50% obstruction [khas land] (m) (409 km)	409000	
Area of tidal channels outside of polders with >50% obstruction [khasland] (m2)	92434000	
Mean depth of khasland channels (m) (5-10 m, bathymetry, KHLC core)	5	
Volume of water that was accommodated in conduit creeks prior to khasland (m3)	**4.62E+08**	462 x 10^6 m^3
TOTAL VOLUME OF WATER REMOVED FROM TIDAL PRISM (m3)	**1.42E+09**	1,420 x 10^6 m^3
% due to khasland	**32.6%**	
% due to obstruction of primary creeks	**18.0%**	
% due to removal of intertidal platform	**49.4%**	
Volume of sediment that has infilled khasland (m3)	4.62E+08	
Mass of sediment that has infilled khasland (MT)	3.56E+08	
Mass of sediment infilling khasland (kg) over 50 yrs	6.15E+11	615 x 10^9 kg
Mass of sediment infilling khasland (MT) over 50 yrs	6.15E+08	615 x 10^6 MT
Annual mass of sediment infilling khasland (MT)	1.23E+07	12.3 x 10^6 MT

Figure 2. Historical satellite imagery was used to identify changes to the tidal channel network in southwest Bangladesh. Obstruction of primary creeks by embankments (black lines in figure top left) and the infilling of several conduit channels outside of embankments (stippled lines in figure top left, khasland in figure bottom left) has had significant repercussions to the tidal prism and sediment distribution (table at right).

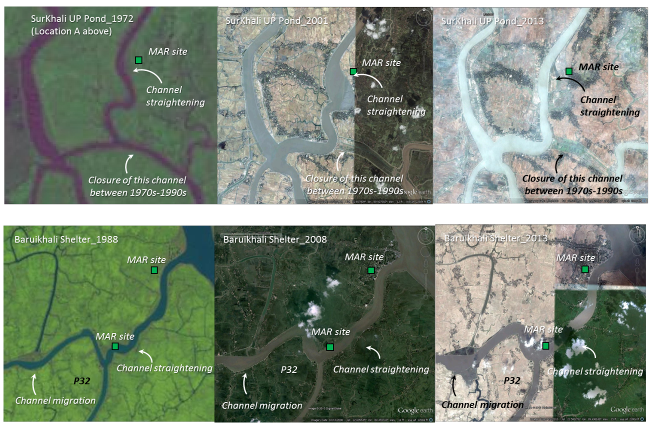


Figure 3. Severing the intertidal platform and large conduit channels from the tidal network appears to have redirected tidal waters to remaining channels, which has possibly accelerated lateral migration and straightening of these channels (focus of future research).

3. Fluvial-Tidal Land surface and hydrodynamics at Natural vs Poldered Areas

Ongoing work in southwest Bangladesh has shown that embanked islands (i.e., polders) in this region lie at an elevation 1-1.5 m below comparable landscapes of the adjacent natural Sundarbans mangrove system (Auerbach et al., *2015*). This phenomenon puts densely-populated polder regions at greater risk to inundation by inefficiently-drained rainwater, and more importantly by tides and storm surges in the case of embankment breaches. This elevation offset is primarily attributed to the obstruction of sediment delivery to the land surface, with added consequences of accelerated compaction due to dewatering of the soils, oxidation of subsurface organic material, and from deforestation and agricultural practices. To date, little data exist on the distribution of surface elevations relative to local water levels, or of sedimentation and compaction rates, either in the polders or natural mangrove system. Additionally, little is known concerning the tidal hydrodynamics that control local processes, such as hydroperiods, suspended sediment concentrations, and current velocities. While it is expected that these dynamics have been significantly affected by poldering and environmental change, little has been quantified or modeled. Better understanding these processes stand to aid in improved placement and management of the embankment systems and help identify the processes and conditions that are most significant to long-term stability of the embankments and landscapes.

Based on these motivating issues, we aim to define the dynamics of landscape development and the transport of water and sediment through local tidal channels, within both the populated polder areas and naturally vegetated Sundarbans mangrove system, incorporating a multi-pronged approach that involves direct measurements of sedimentation, vegetation controls, and channel bathymetry and morphology. Over the past two years, we have deployed an array of Surface Elevation Tables (SETs) along with sedimentation plots and marker horizons in order to better constrain elevation changes, belowground biomass contributions, and compaction rates (Fig 4). Self-contained instruments that record water level, salinity, and temperature (e.g., HOBOs, CTDs) were deployed in many locations to establish an understanding of the local-scale variation in water levels and water characteristics at tidal, seasonal, and interannual timescales. These instruments were deployed in different locations and settings, including open tidal channels and within shallow and deep groundwater piezometers (2.5-inch diameter PVC pipe) located proximal to the SET arrays (Fig 4). In addition, this past year began the quantification of local (reach) scale hydrodynamics by using current meter and ADCP deployments that capture the dynamics from the larger tidal channels to the mangrove platform (work still in progress). Optical Backscatter Sensors (OBS) were used to measure suspended sediment concentration in the water column at the time of current meter (velocity) observations. Preliminary results to date reveal the Sundarbans platform is inundated every spring tide during the monsoon (wet) season (Jun to Oct), however the hydroperiod decreases during the dry season months (Nov to May) and the perched shallow groundwater table lowers (Fig 4). This potentially impacts oxidation potential of the soil, preservation of belowground biomass, and the elevation dynamics (focus of future analyses).

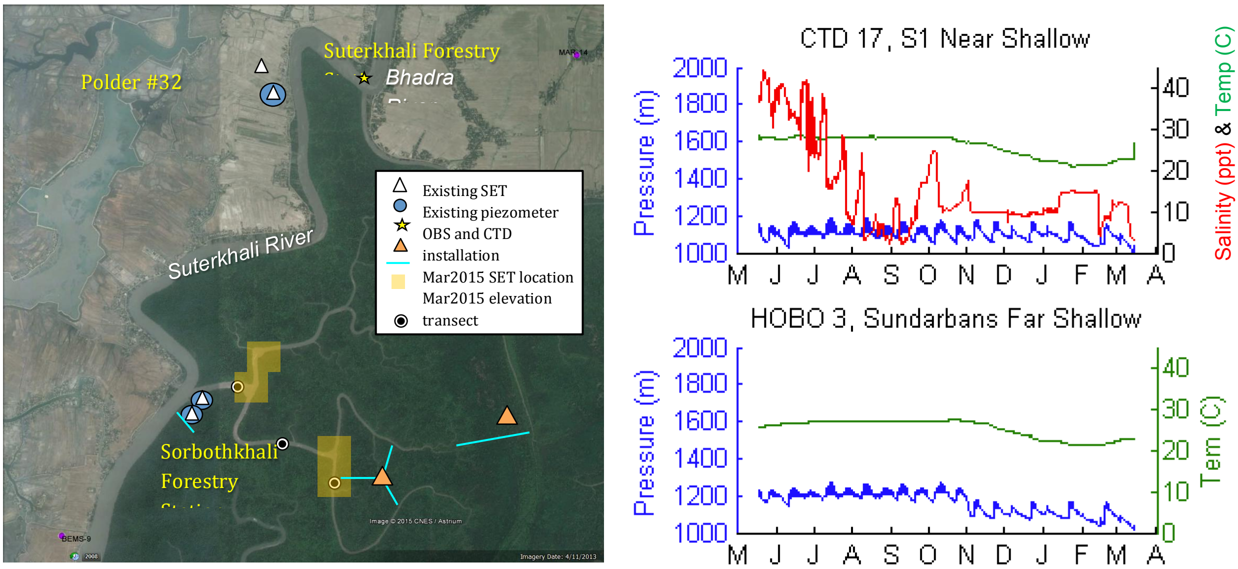


Figure 4. Surface elevation tables (SETs) were installed in 6 locations in both the natural mangrove (N=4) and poldered (N=2) regions of southwest Bangladesh to measure landsurface dynamics, including sedimentation and compaction. Instruments (CTDs, HOBOs, OBS) located inside the tidal channel and shallow piezometers record the surface and groundwater hydrology (e.g., tidal inundation depth, temperature, and salinity) and suspended sediment supply. Results from recent hydrodynamic surveys using current meters (CM) and Acoustic Doppler Current Profilers (ADCP) will elucidate tidal hydrodynamics (ongoing and future research).

Future Research (2015–2016)

In the next year we will continue our observations and database development as described for the Year 2 activities. These field observations are key first steps toward understanding the fluvial and tidal sedimentation and erosion dynamics at the larger- (delta) to smaller- (reach) scale of the G-B delta. Such information is critical for maintaining sustainable natural and human environments, and will also provide necessary inputs for coastal dynamic models such as Delft3D. We also seek to incorporate our results and findings into the Risk Analysis and other portions of the BF-DELTAS project.

Publications 2014-2015 (partially funded by this grant)

Auerbach, L., Goodbred, S., Mondal, D., Wilson, C., Ahmed, K., Roy, K., Steckler, M., Small, C., Gilligan, J., Ackerly, B., 2015. Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change*.

Wilson, C.A., Goodbred, S. L., 2014. Construction and maintenance of the Ganges-Brahmaputra-Meghna delta: linking process, morphology, and stratigraphy. *Annual Review of Marine Science* v 7: 67-88. 10.1146/annurev-marine-010213-135032.

Conference presentations and abstracts:

R. Sincavage, C. Wilson, M. Liang, P. Passalacqua, S. Goodbred, 2015. Comparing morphologic and stratigraphic feld data from a tectonic basin on the Ganges-Brahmaputra River delta with results from a reduced-complexity model for river delta formation. CSDMS annual meeting, Boulder, CO; 25-29 May.

C. Wilson, S. Goodbred, L. Wallace-Auerbach, K. Ahmed, C. Small, S. Sams, 2014. Natural and anthropogenic change in the morphology and connectivity of tidal channels in southwest Bangladesh. AGU Annual meeting, 15-19 December.

C. Small, S. Chiu, D. Sousa, D. Mondal, M. Steckler, S. Akhter, B. Mia, S. Goodbred, C. Wilson, L. Seeber, 2014. Spatiotemporal Dynamics of River Channel Migration on the Ganges-Brahmaputra Delta: 2000-2013. AGU Annual meeting, 15-19 December.

J. Gilligan, B. Ackerly, S. Goodbred, C. Wilson, 2014. Land Use, Livelihoods, Vulnerabilities, and Resilience in Coastal Bangladesh. AGU Annual meeting, 15-19 December.

C. Tasich, S. Goodbred, J. Gilligan, C. Wilson, 2014. Rejuvenating PolderedLandscapes in a Tidally-Dominated, Sediment-Rich Delta: A Numerical Model and Analysis of the Effectiveness of Tidal River Management in Coastal Bangladesh. AGU Annual meeting, 15-19 December.

R. Sincavage, S. Goodbred, J. Pickering, C. Wilson, C. Paola, S. Hossain, M. Steckler, L. Seeber, 2014. Stratigraphic architecture, bedload extraction, and mass balance of Holocene fluvial sediments in a tectonically subsiding basin within the Ganges-Brahmaputra River delta, Bangladesh. AGU Annual meeting, 15-19 December.

C. Peters, G. Hornberger, C. Wilson, S. Goodbred, 2014. Groundwater-Surface Water Interactions in the Poldered Landscape of Southwest Bangladesh AGU Annual meeting, 15-19 December.

C. Wilson, S. Goodbred, I. Overeem, 2014. The importance of scale in defining vulnerability of the Ganges-Brahmaputra River delta to environmental change. Deltas II: Deltas in Times of Climate Change conference, Rotterdam, Netherlands, Sept24-26.

C. Wilson, S. Goodbred, L. Wallace-Auerbach, K. Ahmed, K. Roy, 2014. Human-modified vs natural landscape dynamics in the Ganges-Brahmaputra tidal delta plain. Deltas II: Deltas in Times of Climate Change conference, Rotterdam, Netherlands, Sept24-26.

Eduardo S. Brondizio and Nathan Vogt

Indiana University

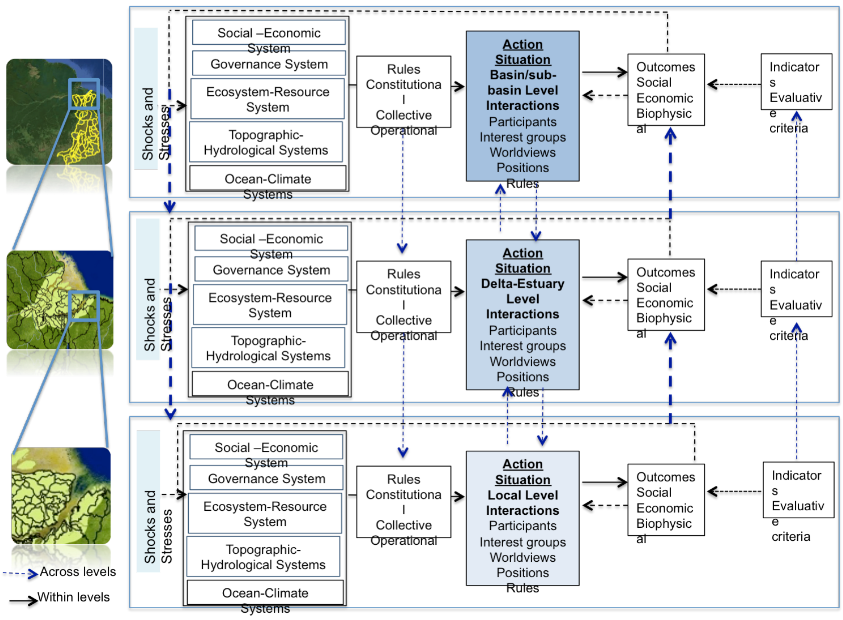
Research Themes and Accomplishments during 2014-2015

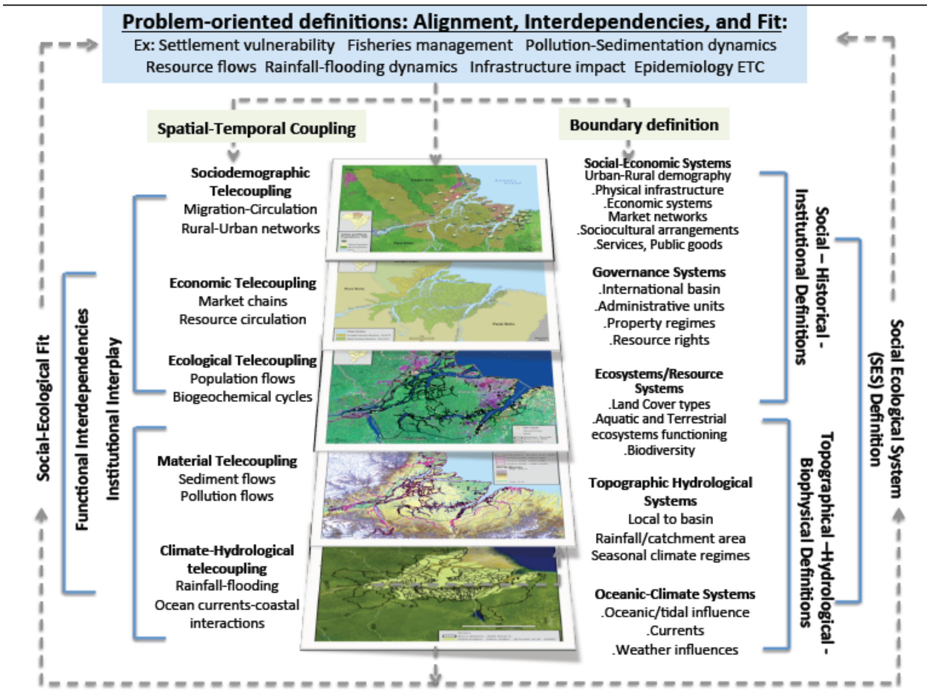
The Indiana University team is completing a very successful second year of the BF-DELTAS project. We have been able to advance and put to use the DELTAS-DAT platform, to involve in research and training two undergraduate students, two graduate students, and two post-doctoral researchers. We have been able to publish and submit several research papers advancing historical analysis of land use change in the Amazon delta, comparative socio-demographic and vulnerability analysis across the three focal deltas of the project, develop a socioecological systems conceptual framework for delta regions, and develop modeling and mapping of vulnerability for urban areas in the Amazon delta. The team has presented these results in several conferences and research meetings. In collaboration with the UNU-EHS team (Bonn, Germany) of the Deltas projects and two regional institutions, we have carried out a successful workshop on co-design and consultation in the Amazon region. This workshop involved 31 participants from the Deltas network and regional universities, governmental and non-governmental organizations. One of the products of the workshop is a proposal for an integrated research agenda for the Amazon estuary-delta region setting a collaborative framework for regional research during the coming decade. A sample of the research highlights produced during the 2014-15 academic year includes (see publication list below).

1. Highlights

-In article to be submitted to *Sustainability Sciences* in June/July 2015 (see Brondizio et al), we propose a problem-oriented socioecological systems conceptual framework for Delta regions, which explicitly integrates biophysical, social, institutional, and ecological variables in the definition and analysis of questions and problems related to delta regions. We use the Amazon estuary-delta region as a basis for the development and application of the framework (see illustrative figures).

Multilevel interaction of Action Arenas in a Estuary-Delta Social Ecological System (SES)





-In an article to be submitted in June/July 2015 to *Nature Climate Change* (see Vogt et al to be submitted *Nature Climate Change*) we show convergence of hydrological and climate evidence and local knowledge of changing flooding patterns in the Amazon Delta This article integrates long-term hydrological measurements and detailed ethnographic research with riverine farmers and fishers in the Amazon (see illustrative figures).

Figure 2. Observed Hydrological Changes in Delta

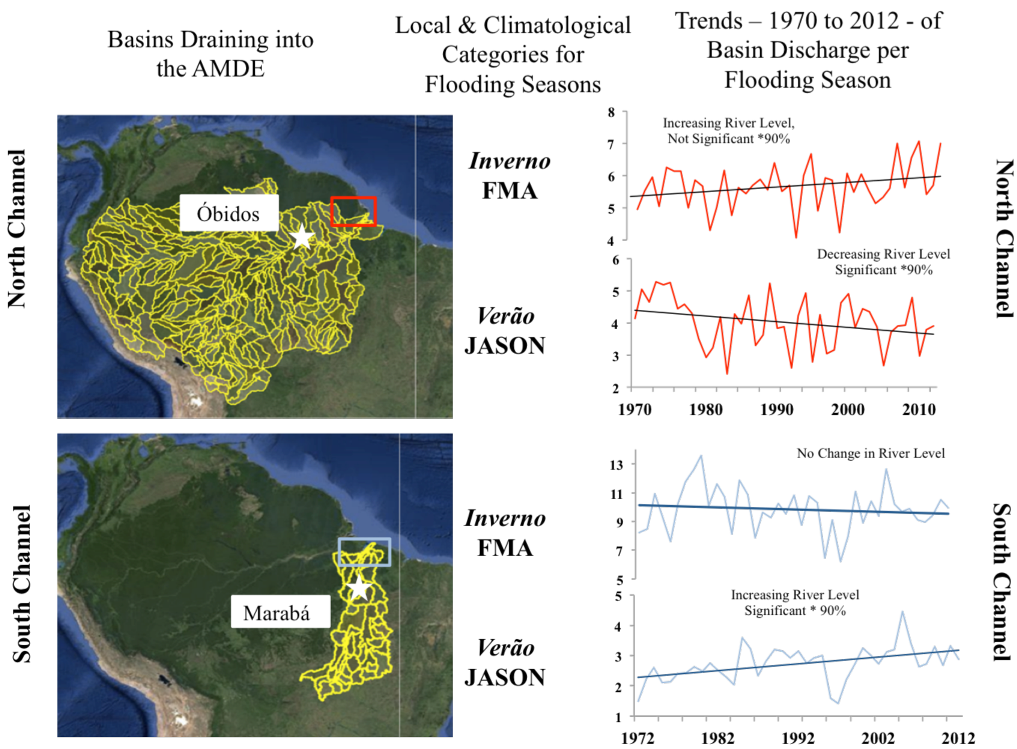
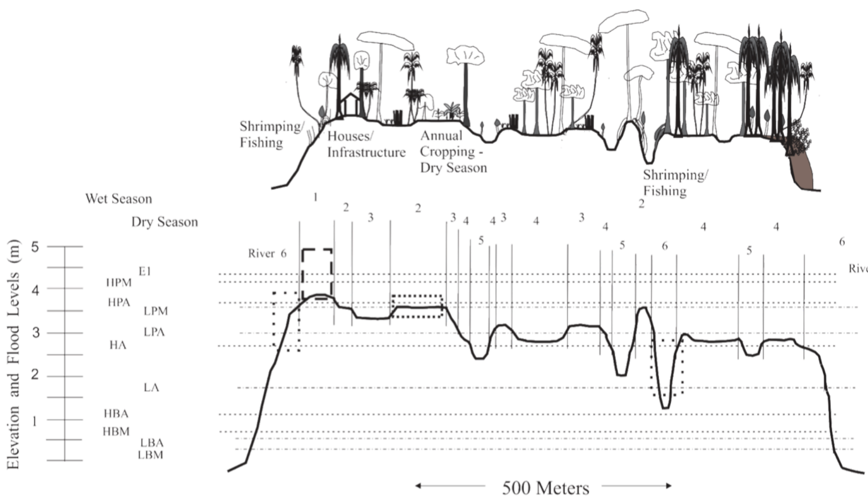


Figure 3. Local Elevation Categories and Sensor Areas of Changes in Flood Pattern



Tide Types and Height per Flood Season			Local Elevation Categories: Salient Spaces for Sensing Change	Change Sensed Decison-Making Rules
Scientific/*Local* Names of Tide Types	Wet Season	Dry Season		
Extreme Events/*Lançante Grande*	E1 4.15 & Above		1 - *Várzea Alto/Tecido* (3.75 - 4.50)	Flood Frequency -Raise/Move Infrastructure
High Tide of Spring Tides/ *Preamar das Aguas Vivas*	HPM 4.04	LPM 3.65	2 - *Várzea Alto* (3.6 - 3.75)	-Delay or Abandon Planting
High Tide of Neap Tides/*Preamar das Aguas Mortas*	HPA 3.72	LPA 3.08	3 - *Várzea Baixo* (3.30 - 3.60)	Current Strength/Erosion -Plant vegetation/habitat
Average River Level	HA 2.80	LA 1.82	4 - *Várzea Baixo/Baixinha* (3.00 - 3.30) 5 - *Igarapé*	
Low Tide of Neap Tides/*Baixamar das Aguas Mortas*	HBA 1.22	LBA 0.57	6 - *Igarapé Poço/Beira do Rio/Prainha*	
Low Tide of Spring Tides/*Baixamar das Aguas Vivas*	HBM 0.80	LBM 0.30		

-In an article published in *Society and Natural Resources* (see Vogt et al 2015), we show how during the last 50 years farmers in the Amazon estuary-delta have adapted to fluctuations in global and regional market demands by maintaining a mosaic of flexible land use systems, while progressively shifting the regional economy from agriculture to forest- and agroforestry-based activities as the dominant land use system in the region today. The article is the first to link 50 years of municipality level census data and multi-temporal remotely sensed data of sample research sites (see illustrative figure).

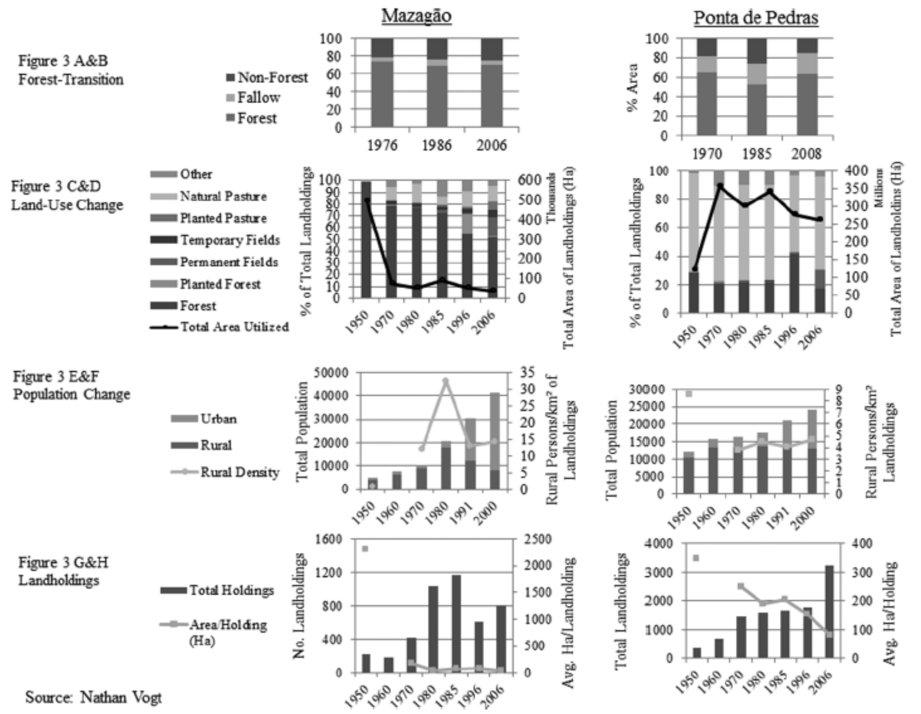


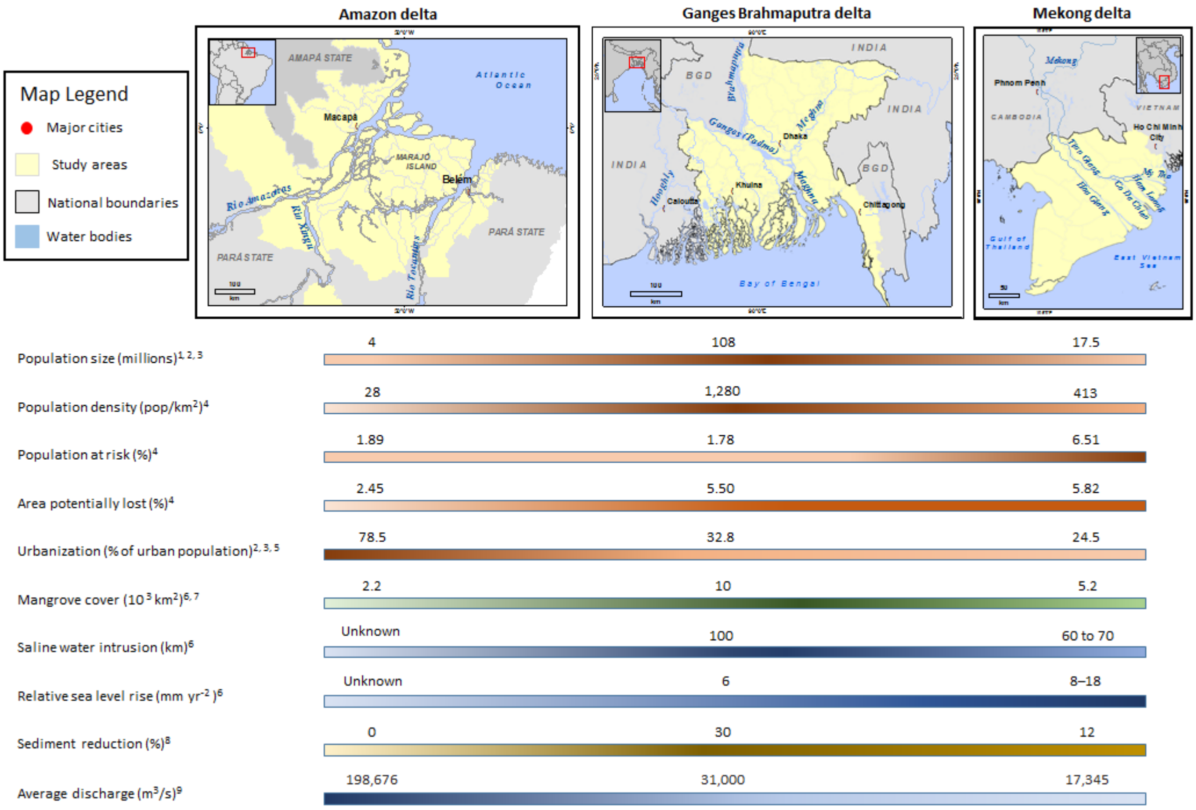
Figure 3. Change in forest cover, land use, population, and number of landholdings in Mazagão and Ponta de Pedras since World War II.

-In an article submitted to *Sustainability Sciences* (see Szabo et al submitted), we have contributed to a comparative demographic analysis of the Amazon, Mekong, and the Ganges deltas, showing that the three deltas have experienced an accelerated demographic transition process and how differences in demographic profiles create different challenges for development and sustainability of each area (see illustrative figure).

-In an article submitted to *Sustainability Sciences* (see Sebesvari et al submitted), a comparative framework and set of indicators for delta vulnerability is proposed for the three study deltas.

-In a report prepared for the Organization Treaty of Amazonian Countries (OTCA) and the UN Convention of Biological Diversity (CBD), Brondizio and Andersson (2014) proposed a conceptual and methodological framework to assess the contribution of local populations to the conservation of biodiversity. The report builds upon research developed in the Amazon estuary- delta region before and during the BF-Deltas project.

-Finally, the two undergraduate students involved with the project have produced research outputs during the 2014-15 academic year: Alejandro Gomez worked with post-doctoral researcher Dr. Nathan Vogt on the “Mini-Atlas” titled *A Spatial-Temporal Evolution of Market Production, Land Tenure and Population in the Amazon Delta and Estuary: 1950 to 2006*. Juan del Valle Coello presented the poster *Do Forest Economies Reduce Deforestation Rates in the Amazon Estuary-Delta?* at the 2015 Indiana University Honors Research Symposium.



2. Update on the DELTAS-DAT

The Deltas-DAT has continued to growth during the second year of the project. It has contributed directly to the preparation of publications and the training of graduate and undergraduate students. Consistent with the goals outlined in objective 3 of the Deltas Belmont Forum Initiative, the IU team consistently assesses datasets acquired and determines data gaps as research progresses.

2.1. Data Acquisition and Processing

In addition to the datasets documented in the 2014 annual report, the IU team has acquired several new datasets and further developed and/or processed those already acquired.

-Socioeconomic/demographic data was collected from the Institute of Applied Economic Research (IPEA) for the years 1990, 2000 and 2010. Tabular datasets from IPEA and INPE were edited for ease of integration with GIS analysis. Data dictionaries were created documenting variable names and definitions.

-Historical data dating back to 1950 documenting urban and rural estuary population and agricultural production was cleaned, graphed and mapped. This dataset served as the basis for the paper published in Society and Natural Resources, as well as preparation of the Szabo et al paper submitted to *Sustainability Sciences*.

-Documentation for Amazon hydrology and basin data acquired from Brazil's national water agency (ANA) continues to be improved in terms of associated documentation.

-Mangrove forest coverage for the Brazil study area was acquired and processed for analysis. Data developed by Giri, C., *et al*. 2011. Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data. *Global Ecology & Biogeography* 20(1):154–159.

-1 arc-second (30m) Shuttle Radar Topography Mission (SRTM) has been acquired. Previously, only 3 arc-second data was available. Data has been processed and mosaicked to cover the Amazon study area.

-Additional datasets at the scale of the Brazilian Amazon documenting geomorphology, climate, and land use have been acquired.

-Doctoral student Andressa Mansur produced a map of urban vulnerability for the region, which has been now integrated into the Deltas-DAT system.

2.2. Deltas-DAT support for manuscript preparation and data visualization

The Indiana group provided support for four of the papers submitted to the special issue for *Sustainability Sciences*. This support includes text and figures describing the historic demographic context of the Amazon study area, map products of all three demonstration deltas, and a figure which visualizes population-environment gradients associated with urban vulnerability in the Amazon study area. Much of the content used for the analysis supporting this paper is a result of data acquired since the last annual report.

As stated above several map products and figures have been produced in support of project papers and to help team members visualize the Amazon Delta definitions, features within the study area, hydrology and delta basins, and topography. In addition, several poster-sized maps were created and plotted to support the BF-Deltas workshop held in Belém, Brazil, May 2015.

2.3. Utilization of the iRODS server and iDROP interface

As reported in the 2014 annual report the IU team worked closely with Zach Tessler at CCNY in testing the iRODS server and iDROP interface and helped to encourage the use of the server for data storage and dissemination. iRODS/iDROP provides middleware between (several) physical data storage systems and an effective, efficient user interface. The iRODS/iDROP system is now widely used as a shared data repository for all demonstration deltas. Relevant datasets and metadata continue to be uploaded.

3. Co-Design and Consultation Workshop

Following a similar methodology as organized in the Ganges and the Mekong, under the leadership of BF-Deltas partners Zita Sebesvari and Fabrice Renauld from the UNU-EHS, a consultation and co-design workshop was organized in the city of Belem (Para State) in the Amazon Estuary-Delta (May 12-13, 2015). The workshop “BF-DELTAS stakeholder consultation for the development of a Global Delta Vulnerability Index (GDVI) - Amazon Delta” was organized in collaboration with two leading research institutions, the Emilio Goeldi Museum and the Federal University of Para (UFPA) .

A total of 31 participants representing government, non-governmental, and research institutions from the states of Para and Amapa participated. The workshop was considered a great success. Three main sets of products were generated and are currently under preparation. First, we developed a participatory mapping exercise to sub-divide the Amazon estuary delta into sub-regions followed by the identification of current and emerging social and environmental problems. Second, diagrams of impact and identification of indicators were developed for each category of problems identified. Third, the group discussed and defined a list of priority research areas for research and collaboration with stakeholders. This exercise generated an initial proposal for an integrated research agenda for the region. A first draft of the proposed research priorities has been circulated to the participants for discussion and editing. The agenda will be used to mobilize collaborations and resources for a ten-year integrated research program in the region.

4. Outreach: Museum Exhibit

Brondizio has co-curated with A. Siqueira (Indiana University) a museum exhibit focusing on the globalization of the acai fruit/agroforestry economy of the Amazon estuary-delta. The exhibit “*Acai from local to global*” has been under exhibition at the Mathers Museum of World Cultures, Indiana University since August 19, 2014. It includes 20 photographic panels and over a 100 items showing the globalization of the acai palm fruit and its relationship to local populations, economy, and development in the Amazon estuary-delta region. The Exhibit was a part of the IU’s College of Arts and Sciences ‘2014 Themester’ on ‘Food for Thought’.

Concluding remarks and future work

The academic year 2014-15 has been very productive for the Indiana University team. We have accomplished our goals in advancing the Amazon Deltas-DAT system, of capacity building (particularly in terms of incorporating undergraduates into the project) and advanced several publication goals.

During the last year of the project we will focus on the following activities: -We will continue to focus on capacity building and student mentoring, with particular emphasis on mentoring students to lead research articles associated with the project.

-We will continue to prepare research articles using project data from the Amazon Deltas-DAT and comparative analysis with the other two study sites.

-We will complete the data process of the consultation and co-design workshop carried out in the Amazon with the goals of producing new manuscripts and finalizing the proposal for a research agenda for the Amazon estuary-delta.

-Finally, we will focus on making the Deltas-DAT system available to regional institutions in the Amazon and, if possible, develop an online platform to share the Deltas-DAT more broadly.

Publications

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Meetings And Conference Presentations [Using research examples from the BF-Deltas project]

Brondizio, E. S. [workshop participation] UNU-Tokyo. *IPBES and ScenNET Workshop on Participatory Scenarios*. United Nations University and UNESCO. United Nations University, Tokyo, June 15-16, 2015.

Brondizio, E. S. Keynote: Land use and the Future Earth Strategic Research Agenda. *International Conference on Carbon Cycle and Global Change*. Zhejiang A&F University, Lin An, Hangzhou, China, June 10-12, 2015.

Brondizio, E. S. [panel presentation]. Panel: Working Across Scales to Understand the Earth System at the *International Symposium Integrated Science for Sustainable Transitions*. International Institute for Applied Systems Analysis (IIASA) and the International Geosphere Biosphere Programme, IIASA, Laxemburg, Austria, April 29, 2015.

Brondizio, E. S. [paper presentation] Complexity and landscape governance in the Amazon and Panel co-organizer Matching the mismatches: linking scales in the Amazon. *2015 Annual Meeting of the American Association of Geographers* (AAG), Chicago, April 21, 2015.

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Brondizio, E. S. [Workshop participation]. Building capaticy for 21st. Century social sciences. NSF-supported planning meeting, March19-20, 2015, Washington, D.C..

Brondizio, E. S. Plenary talk. From sustainable land uses to sustainable rural economies: Innovations and structural constraints. *5th International Conference on Sustainability Science*. United Nations University and the University of Tokyo, 22-24 January 2015, Tokyo, Japan.

Brondizio, E. S. Workshop presentation. Cultural dimensions of insurance value of ecosystems. *Workshop on the Insurance Value of Ecosystems*. United Nations University (UNU, Tokyo) and the Stockholm Resilience Centre (Sweden). 21 January 2015, Tokyo, Japan.

Brondizio, E. S. Discussant. Panel: Spinning Anthropology in the Anthropocene: Why and How We Must Integrate Theoretical and Applied Approaches to Meet Contemporary Challenges. *2014 Annual*

Meeting of the American Anthropological Association. December 4, 2014 Washington, D.C..

Brondizio, E. S. Invited talk. Evolutionary governance for land Stewardship. Columbia University and the Center for International Forest Research [CIFOR] *Colloquium on Forests and Climate Change: New Thinking for Transformational Change,"* [streamed live internationally]. Parallel event to the New York Climate Summit of the UN.

Brondizio, E. S. Invited talk. Uso da Terra e Aceleracao de Mudancas Sociais na Amazonia: Uma Perspectiva a partir de Sistemas Complexos. Universidade Federal do Para, Belem, Para, June 26, 2014.

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Claudia Kuenzer and Benjamin Mack

University of Wuerzburg

Research Themes and Accomplishments during 2014-2015

The focus of the research efforts over the past year have concentrated on (1) the development and implementation of automatic pre-processing and feature extraction capabilities for optical high-resolution (HR) remote sensing data (10-30m) and (2) the derivation of a high-resolution land use/land cover (LULC) classification for the Ganges-Brahmaputra river delta (GBD) for the year 2014. Furthermore, an animation called *River Deltas* has been produced in cooperation with the Science Communication and Visualization department of the German Remote Sensing Data Center, German Aerospace Center (DLR) (http://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-10013/#gallery/25551). Finally, a manuscript has been prepared and submitted to *Remote Sensing* in which the potential of coarse spatial resolution, temporally-dense MODIS time series is investigated for the mapping of inundation patterns in river deltas.

1. Automatic processing of high-resolution optical remote sensing data

Remote sensing data is an important data source for the retrieval of spatially explicit information such as land use/land cover (LULC). The spatial resolution of the retrieved maps is of critical importance for the users. With the opening of the Landsat archive a large amount of high quality high spatial resolution data became freely available. In the near future the Sentinel-2 with similar spectral and spatial properties will further increase the availability of HR data. At the same time digital processing and data storage capabilities have improved. As a result, nowadays large areas can be mapped at high spatial resolution where in the past only medium/coarse resolution data (>300m) has been used for such purposes. A further advantage of Landsat data is the availability of historic data allowing the analysis of change processes over more than three decades.

Exploiting the full potential of the whole available data is expensive in terms of processing cost and requires automatic routines for image pre-processing and feature extraction. Therefore, an automatic processing chain has been implemented in python in order to explore the potential of HR remote sensing data for information retrieval for the demonstration deltas. Figure 1 shows the general flowchart of the processing chain from the image selection to the resulting map product. The processing chain consists of four main processing units: i) Query and download source images, ii) pre-processing source images, iii) extraction of regionally consistent features, and iv) information retrieval, e.g. classification.

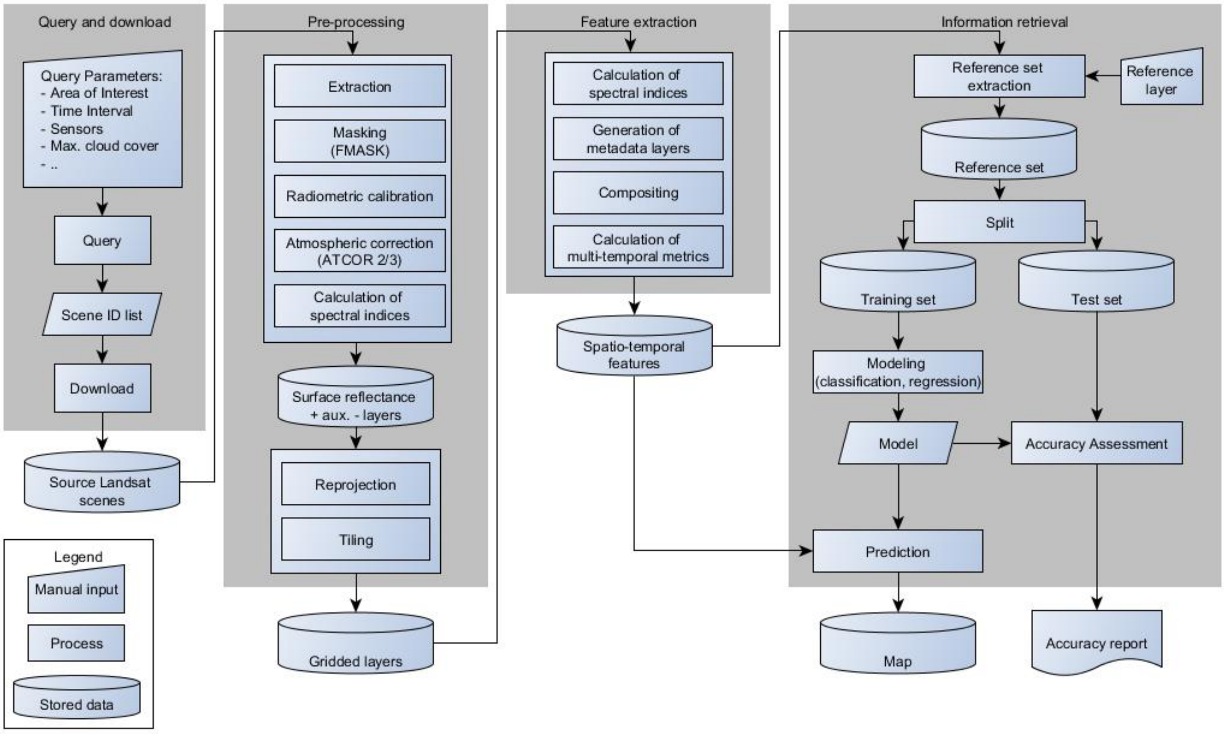

Figure 1. Implemented processing chain for high spatial resolution mapping.

First, the source images to be processed for a particular mapping application are queried from the metadata database given search criteria such as the area of interest, the date range, etc. All images meeting the search criteria are downloaded. The pre-processing steps are applied on all source scenes individually. This includes the calculation of a cloud/cloud-shadow mask (based on FMASK (Zhu and Woodcock 2012), radiometric correction and atmospheric correction (based on ATCOR 2 or 3). The preprocessed data layers (mask, top-of-atmosphere and/or at-surface reflectances) are then projected in a common reference system, tiled and stored as gridded raster data with strictly aligned pixel locations.

Due to different acquisition times and cloud cover each pixel corresponds to an irregular time series of valid observations. Data aggregation is required in order to extract a regionally consistent set of features (without data gaps) that can be handled by common information retrieval methods, such as supervised classification and regression algorithms.

One option is to generate one or more cloud/cloud shadow free composites. Therefore, at each pixel location the 'best' observation is selected based on some compositing criteria. We have implemented an algorithm similar to the WELD algorithm (Roy et al. 2010) which – among other selection criteria – makes use of the maximum NDVI and maximum brightness temperature compositing criteria. Additionally or alternatively, multi-temporal metrics can be derived from the time series. Such metrics have proven to be very informative for classification (Potapov et al. 2014). We derived metrics based on ranking of the reflectance, brightness temperature and spectral index values, i.e. values representing the 10, 25, 50, 75 and 90% percentiles, as well as inter-quartile ranges (75% percentile-25% percentile) and central 80 % ranges (90% percentile-10% percentile). Finally, the spatially consistent features can be used in combination with labeled reference data for supervised statistical learning methods, e.g. a classification algorithm for the retrieval of LULC information.

2. Land cover classification for the Ganges-Brahmaputra river delta

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. We have used the implementation described in the previous section for the generation if a LULC map of the GBD for the year 2014. The area of interest overlaps with twelve Landsat path/rows. We downloaded all Landsat-8 and Landsat-7 images with less than 50% cloud cover between the 1st of December 2013 and the 31st of May 2014. A total of 214 Landsat scenes (Landsat 7/8: 106/108) met the search criteria and have been processed with the implemented processing chain.

We derived several composites for the area of interest. For the whole date range, a sufficient number of acquisitions have been present for the generation of a single gapless composite (Figure 2). However, a lot of (temporal) information is lost when only a single composite is used.

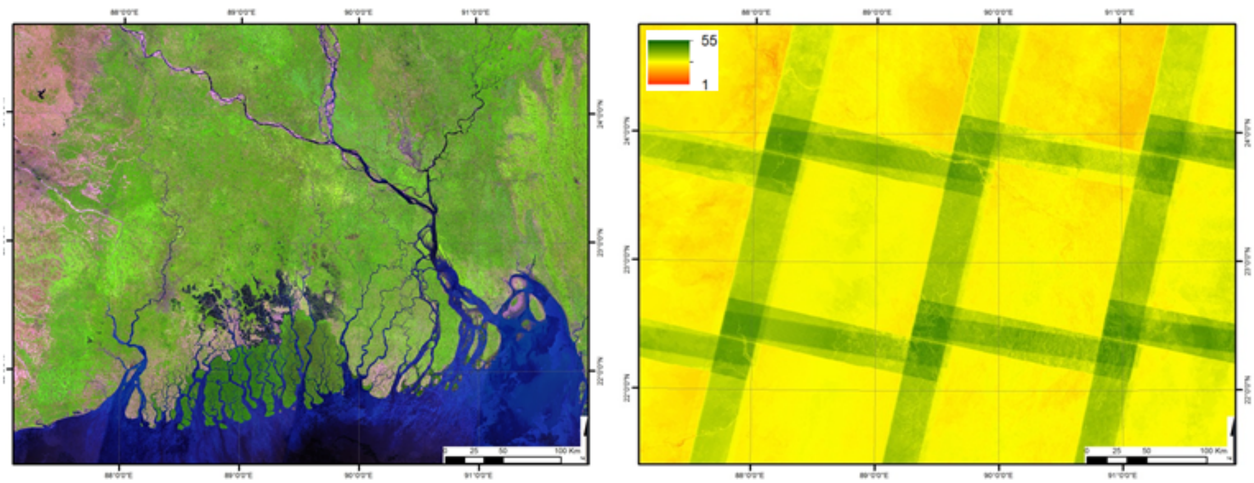

Figure 2. Color composite (R: SWIR1, G: NIR, B: RED) of the 'best' pixel composite derived from the whole data set (left). Number of clear (cloud/cloud shadow free) acquisitions per pixels (right).

Therefore, monthly composites have also been created (Figure 3). They depict the spectral variation over the date range and therefor contain more information. On the other hand, there are data gaps in some of the monthly composites and if the whole area reeds to mapped they cannot be used with common supervised algorithms for LULC classification. We selected the monthly composites (surface reflectance and NDVI) with full coverage (02/2014, 03/2014, 04/2014) as input features to the classification algorithm.

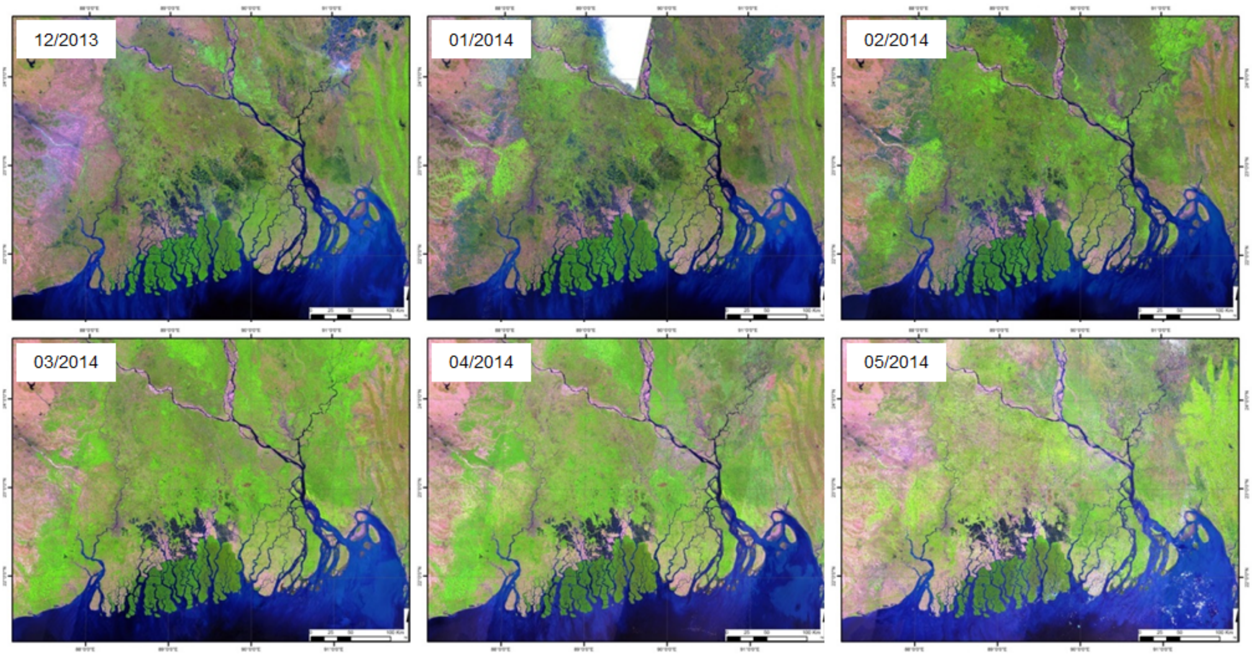

Figure 3. Monthly 'best' pixel composites of the GBD. For some month (12/2013, 01/2014, 05/2014) show data gaps, i.e. regions which were cloud covered in all acquisitions (see also Figure 4).

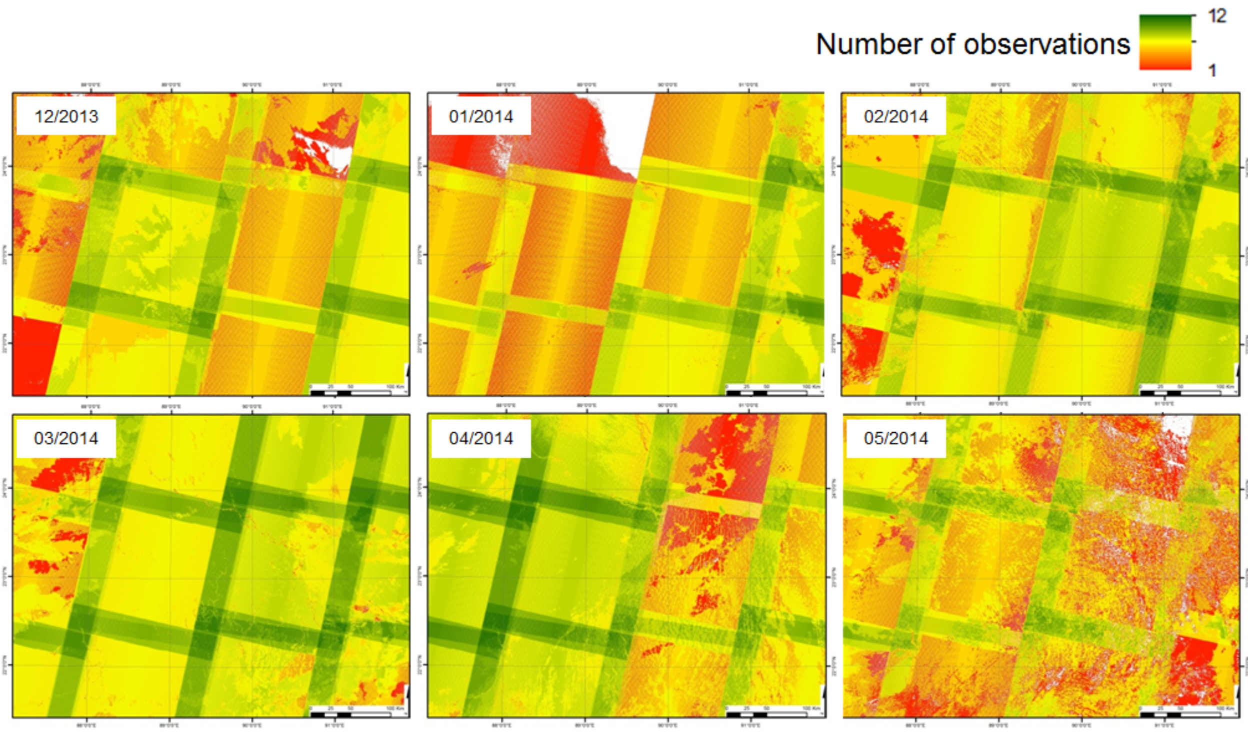

Figure 4. Number of clear (cloud/cloud shadow free) observations available for the monthly composites (see Figure 3).

Eight LULC classes have been mapped: settlements, agriculture, woodland, mangroves, sandbanks, mudflats, wetlands and water. For these classes 1321 reference polygons have been manually digitized by visual interpretation of the Landsat and GoogleEarth images (Figure 5). The random forest classifier has been used for classification. Due to separability problems with the class 'settlements' it has been removed from the classification process. Instead, the Global Urban Footprint has been overlaid on top of the classification result. Figure 5 shows the classification result. A first visual assessment of the classification is encouraging.

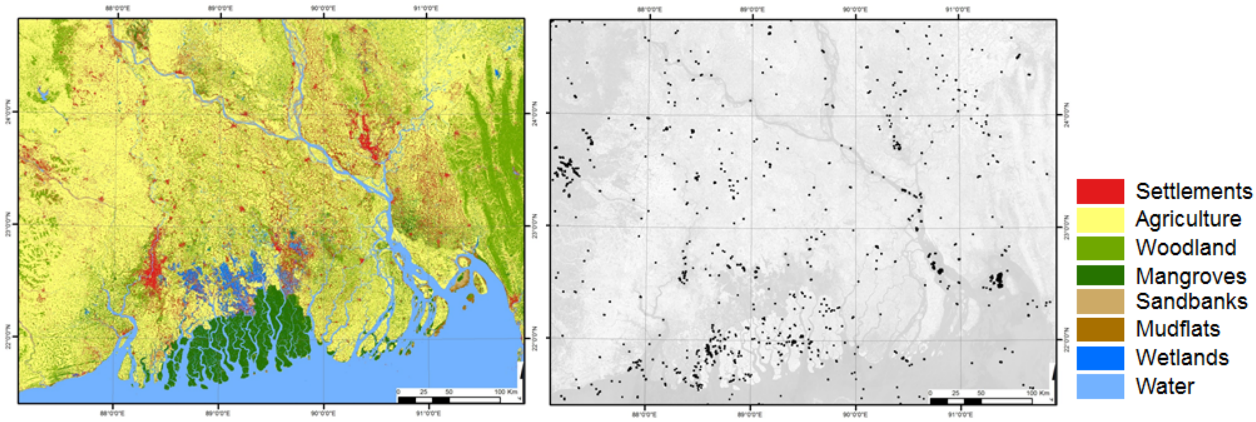

Figure 5. Classification result (left) and training polygons used for training the classifier (right).

As described above, we have started to implement different multi-temporal features which, however, have not been used for classification so far. Multi-temporal features extract the temporal spectral variation but it is not required to define temporal (sub-) ranges (e.g. months) for different composites. Consequently, the problem of data gaps is less probable while the information content with respect to LULC classes is eventually higher. Figure 6 shows a false color composite of multi-temporal features. It is evident, that a lot of information is contained in only these three features. The next step is to evaluate the multi-temporal and spatial/texture features for classification and identify a suitable feature set.

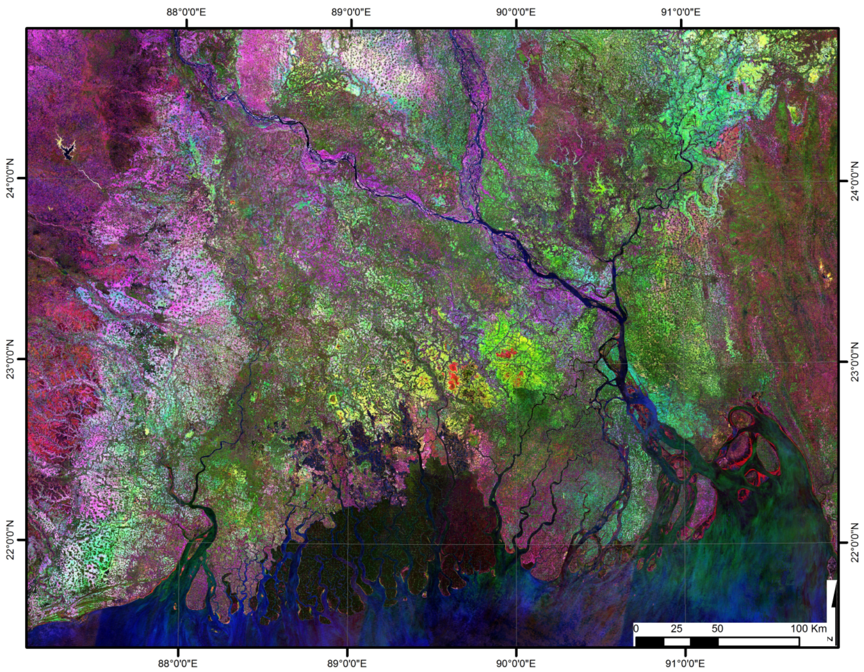

Figure 6. False color composite of the inter-quartile ranges of the reflectance layers SWIR1 (R), NIR (G), RED (B).

Future Research 2015-2016

1. Extension of multi-temporal metrics: Particularly, spatial metrics and image texture will be implemented and investigated and is assumed to be particularly important for heterogeneous classes such as *urban*.

2. Algorithm driven support of reference data selection: Active learning is an interesting research area in the field of pattern recognition and is based on the assumption that the acquisition of reference data can be solved more efficiently when the samples (pixels/polygons) to be labeled by the human expert are selected by an algorithm. Particularly in the case of large area mapping this can accelerate the mapping process where the collection of reference data is the most time and labor intensive step.
3. Compilation of further land-cover/land-use change products for the demonstration deltas.

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Research Themes and Accomplishments during 2014-2015

1. Development of a theoretical framework

The selection and adaptation of the theoretical framework was an iterative process. Based on the review of frameworks used for social-ecological vulnerability assessments, a simplified yet inclusive multi-hazard SES vulnerability assessment framework – the Delta-SES-framework – is proposed (Figure 1).

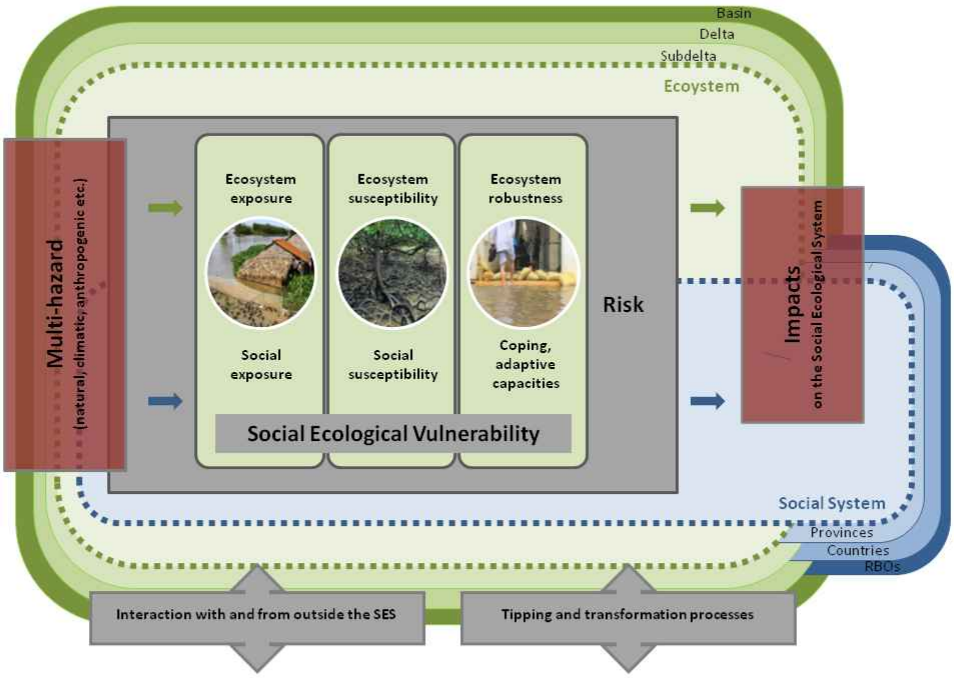


Figure 1. Deltas-SES-framework (source: authors based on *Turner et al. 2003a*, *Damm 2010*, *Garschagen 2014*, *Kloos et al. 2015*)

The Deltas-SES-Framework synthesizes key, relevant elements of some previously used frameworks by:

1) Focusing on the SES and acknowledging different spatial scales (Turner et al. 2003a), here from sub-delta to basin scale for the ecosystem and from districts/provinces to countries or river basin organizations (RBOs) for the social system,

2) Considering ecosystem robustness as one of the sub-domains (Damm 2010);

3) Referring explicitly to multi-hazard settings and acknowledging tipping and transformation processes (Kloos et al. 2015), and

4) Considering not only natural but also anthropogenic hazards (IPCC 2012, Garschagen 2014).

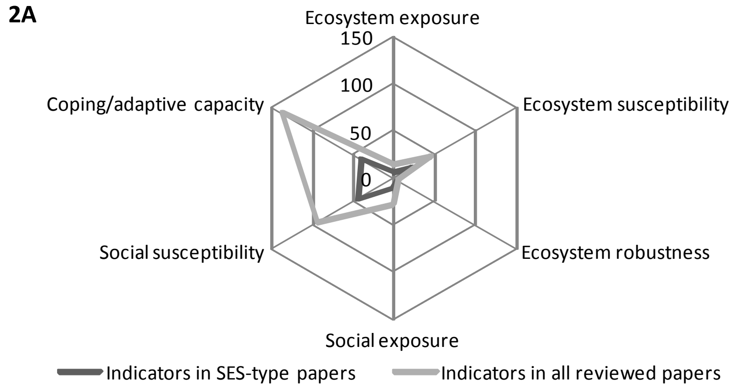
In the Delta-SES-framework, the social and ecological sub-systems are intersecting each other and are characterized by interactions and feedbacks at various temporal and spatial scales. Although all scales are relevant and interact with each other, the essential place of the analysis is considered to be the sub-delta scale to account for the differences in vulnerability among delta sub-regions, e.g. coastal zones, floodplains, and urban areas. Several natural and/or anthropogenic hazards might occur at the same place, leading to interactions among hazards and impacts and/or to cascading events or impacts (red boxes in Fig 1). The nature and magnitude of the hazard(s) as well as the vulnerability of the SES determines the impacts experienced by the SES or its sub-systems but also the risk to experience harm. Hazards might originate within a given SES (e.g. water pollution) but can also be generated outside the SES (e.g. global sea level rise). These interactions from outside as well as SES-internal processes might lead to transformations and tipping processes which greatly influence the vulnerability context (grey boxes in Fig 1). For the definitions of the major framework elements see Table 1.

Table 1. Definitions of the framework elements used in the Deltas-SES-Framework. Definitions adapted from *IPCC 2012*, *Renaud et al. 2013*, *Garschagen 2014* and *Jen 2003*.

Term	Definition used in the Deltas-SES-framework
Hazard	The potential occurrence of sudden onset or slow natural, anthropogenic or coupled physical events or processes that may cause loss of life, injury, or other health impacts, as well as loss and damage to elements and processes of the social-ecological system in place.
Multi-hazard	The different hazards occurring at the same place either at the same time or consecutively and either mutually or one directionally influencing the hazard´s impact on the SES.
Disaster risk	The potential of severe alterations in the normal functioning of elements and processes within the SES due to the interaction of one or multiple hazards interacting with vulnerable elements or conditions of the same SES, leading to a potentially wide range of adverse effects.
Vulnerability	The predisposition of the elements and processes of the SES to be adversely affected. Vulnerability is composed of exposure, susceptibility and lack of capacity to cope, adapt or recover.
Exposure	The extent to which elements and processes of the SES are in the reach or subjected to hazards.
Susceptibility	The internal predisposition of an element to suffer a certain degree of harm when exposed to a hazard.
Coping capacity	The ability of people, organizations, and systems, using available skills, resources, and opportunities, to address, manage, and overcome adverse conditions with the aim of achieving basic functioning in the short to medium term.
Adaptive capacity	The strengths, attributes, structures, resources available to an individual, community, society, or organization that can be used to prepare for and undertake actions to strategically reduce exposure, susceptibility and adverse impacts as well as enhance capacities in the long run.
Ecosystem robustness	The existence of a set of “strategic options" open to the ecosystem and the capability of the ecosystem to switch among multiple functionalities.
Tipping point	A breakpoint between two regimes or states, which is reached when major and controlling variables of an SES no longer support the prevailing system and the entire system shifts in a different state, which is distinct from the previous state and recognizable with specific characteristics. The change can be sudden (e.g. external shocks) or gradual (changes in underlying drivers) and can be induced by changes in both the social and the ecological part of the system.

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

The Delta-SES-Framework provided a structure for the review of vulnerability indicators used in assessments in the three model deltas. In total, 305 indicators were identified and included in respective vulnerability domains. Based on the reviewed studies, we noted a lack of previously proposed indicators to populate some of the vulnerability domains of our framework as comprehensive social-ecological assessments were seldom implemented. Even in assessments explicitly aiming to capture both sub-systems, indicators for social susceptibility and coping/adaptive capacities overwhelmed those for the ecosystems (Figure 2A and 2B). Clearly, more effort is needed in the future to truly integrate ecological and social indicators in assessments for delta environments. Moreover, there is a lack of multi-hazard approaches accounting for the specific vulnerability profile of sub-delta areas. Future assessments could use our proposed framework and reviewed list of indicators as a basis for more comprehensive vulnerability assessments at a sub-delta scale and to also identify new indicators that would allow capturing the complexity of delta SES.



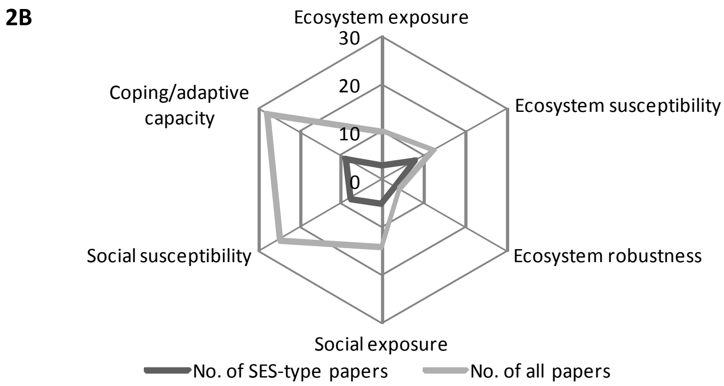


Figure 2. A. Comparison of the number of indicators dealing with the six vulnerability domains in SES-type papers vs. all reviewed papers. B. Comparison of the number of papers providing one or more indicators for the six vulnerability domains for SES-type papers vs. all reviewed papers.

3. Identification of indicators by stakeholders in all three model deltas

The purpose of the "BF-DELTAS expert consultations on delta vulnerability indicator selection" was to gather inputs and opinion of various stakeholders on current and future hazards and vulnerabilities at the sub-delta (upper, middle, coastal) level. While the first consultation was organized already in April 2014 and thus in the first project year, the second and the third consultation was held in

September 2014 and in May 2015. The workshops gathered experts from across the natural and social sciences disciplines and from science and governmental organizations, from NGOs, as well as independent experts. The participants familiarized themselves with vulnerability concepts, frameworks and indicators and provided their insights into current and future hazards as well as exposure, sensitivities and coping/adaptation capacities under selected hazards. The indicators complement the outcome of the indicator review process and feed in into the development of the final indicator set.

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Future Work (2015–2016)

Research activities:

Guided by the conceptual Delta-SES-framework and based on the outcomes of both the systematic literature review and the outcomes of the stakeholder workshops in the three model deltas, a flexible set of vulnerability indicators is currently being developed which can then be combined for deltas globally in a modular way. Taking the given (multi) hazard profile of the respective delta as an entry point for the selection of appropriate vulnerability indicators, the modular structure allows being responsive to the idiosyncrasies of a delta SES while also considering the interactions between the hazards in a given location. The final set of indicators, comprising both hazard-specific and non-specific indicators, is an important step towards the development of a Global Delta Vulnerability Index (GDVI) and will serve as a basis for spatially explicit vulnerability assessments in the three model deltas. Geospatial data from both global data repositories and national data providers is currently collected for the three case study regions and will be used to populate the different components of the Delta-SES-framework. Following data pre-processing routines (i.e. analysis and treatment of missing data, outliers and multicollinearities in the data), all datasets will be normalized before they are combined in an integrated vulnerability index that enables capturing the spatial variability of vulnerability of the SES at sub-delta scale.

Conferences:

- Dr Fabrice Renaud currently co-organizes the session “Sustainable Deltas: Multidisciplinary Analyses of Complex Systems“ at the American Geophysical Union Annual fall meeting 2015 in San Francisco, USA
- Dr Zita Sebesvari submitted the following abstract to the above mentioned session: Development of Vulnerability Indicators for Deltaic Social-Ecological Systems Facing Multiple Environmental and Anthropogenic Hazards by Zita Sebesvari, Michael Hagenlocher, Susanne Haas, and Fabrice Renaud.

Others:

- Dr Fabrice Renaud and Dr Zita Sebesvari will contribute regularly to the DELTAS cyber-seminars;
- Dr Fabrice Renaud will continue his work as a guest-editor of a special issue “Sustainable Deltas: Livelihoods, Ecosystem Services and Policy Implications” in the Springer journal “Sustainability Science” (to be published in 2016)
- Dr Fabrice Renaud will advance the planning of a high-level science to policy meeting in the United Nations (UN) headquarters in New York City in 2016.

Publications

Sebesvari, Zita, Renaud, Fabrice G., Haas, Susanne, Tessler, Zahary, Kloos, Julia, Szabo, Sylvia, Tejedor, Alejandro, Kuenzer, Claudia. Vulnerability indicators for deltaic social-ecological systems: a review. Submitted to Sustainability Science in July 2015

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Presentations

Presentation on “Global delta vulnerability indicator development” at the Deltas in Times of Climate Change II conference in September 2014 in Rotterdam, Netherlands.

Presentation “Changes in Ecosystem Services and related Livelihoods in the Mekong Delta: vulnerabilities and adaptation strategies” at the American Geophysical Union Annual fall meeting in December 2014i n San Francisco, USA.

Fabrice Renaud and Zita Sebesvari (2014) “Global delta vulnerability indicator development”, Deltas in Times of Climate Change II conference, September 2014, Rotterdam, Netherlands (oral presentation).

Zita Sebesvari and Fabrice Renaud (2014) “Data for vulnerability assessments: Problems of accessibility and availability”, Deltas in Times of Climate Change II conference, September 2014, Rotterdam, Netherlands (oral presentation).

Zita Sebesvari and Fabrice Renaud (2014) “Changes in Ecosystem Services and related Livelihoods in the Mekong Delta: vulnerabilities and adaptation strategies”, American Geophysical Union Annual Fall Meeting, December 2014, San Francisco, USA.

Edward Anthony

Aix-Marseille University

Research Themes and Accomplishments during 2014-2015

The AMU team has been involved in the Cross-Cutting Work Package and conducted research on the sediment dynamics and shoreline changes of the Mekong delta (*Anthony et al., in revision*), Amazon mouth (*Gensac et al., in revision*) and Amazon-influenced Guianas coast (*Walcker et al., in press*; *Brunier et al., submitted*), and more lately, in 2015, the Ganges-Brahmaputra delta (*A. Ricout, Master's dissertation June 2015*).

1. Shoreline changes in the Mekong delta

The delta shoreline changes since 1973 have been mapped from satellite data. For the most recent period between 2003 and 2014 (Fig. 1), over 50% of the >600 km-long delta shoreline is eroding, generating significant land loss along the muddy South China Sea and Gulf of Thailand coasts that are raising increasingly alarming concerns in Vietnam (Anthony et al., in revision). The Mekong delta coast has lost nearly the equivalent of one football field every day between 2003 and 2012, the net loss rate being still mitigated by the sandy delta mouth sector which shows mild net accretion. Loisel et al. (2014) showed in their MERIS-based analysis of coastal waters under the Mekong's influence that notwithstanding strongly seasonal variability, there was a robustly determined long-term trend of about −5% in suspended particulate matter concentration per year between 2003 and 2012 that they attributed to a persistent decrease in Mekong river sediment output during the critical high-flow season when the river supplies sediment to the sea. Loisel et al. (2014) concluded that the hydrodynamic forcing showed no significant changes over the period of analysis, and Brunier et al. (2014) found no significant changes in Mekong liquid discharge likely to explain the 5% annual drop in the Mekong's suspended sediment supply to the South China Sea between 2003 and 2012. Although the recent persistent decrease in SPM concentrations off the delta shown by Loisel et al. (2014) is very likely related to dam impoundment of sediment, the reservoir sediment retention issue, which has come to the fore in recent years, and its downstream impacts, are susceptible to debate because of the poorly constrained Mekong river load. Commercial riverbed mining has also been practised on an increasingly larger scale over the last decade, driven by strong development pressures, especially in Cambodia and Vietnam (Brunier et al., 2014). Another problem is that of accelerated sinking caused by water extraction, generating delta enhanced exposure to sea-level rise and flooding (Erban et al., 2014). Considering shoreline stability in terms of a balance between available incident wave energy and available sediment, we interpret (Anthony et al., in revision) the shoreline change patterns, and notably the rampant erosion of the more wave-exposed South China Sea coast, as the outcome of a decreasing Mekong River sediment supply to the sea in the context of a relatively energetic dry-season wave-energy regime and longshore transport system.

2. Suspended particulate matter dynamics at the mouth of the Amzon and downdrift mangrove changes on the Amazon-Orinoco coast

Fine-grained sediments supplied to the Ocean by the Amazon River and their migration under the influence of continental and oceanic forcing drives the geomorphic change along the 1500 km-long coast northward to the Orinoco delta. SPM concentrations were calculated from satellite products (MODIS Aqua and Terra) acquired over the period 2000-2013 (Gensac et al., in revision). Sediment shows alternating accumulation and resuspension patterns associated with seasonal Amazon River discharge flushing processes. A 150 km-long area of accretion is detected at Cabo Norte that may be linked with a reported increase in Amazon River sediment discharge concurrent with the satellite data study period. We also assess the mud bank migration rate north of Cabo Norte (Fig. 2), and highlight its inconstancy. Although we confirm a 2 km.y^{-1} migration rate, in agreement with other authors, we show that this velocity may be up to 5 km.y^{-1} along the Cabo Orange region, and highlight the effect of liquid discharge by major rivers debouching on this coastal mud belt in modulating such rates.

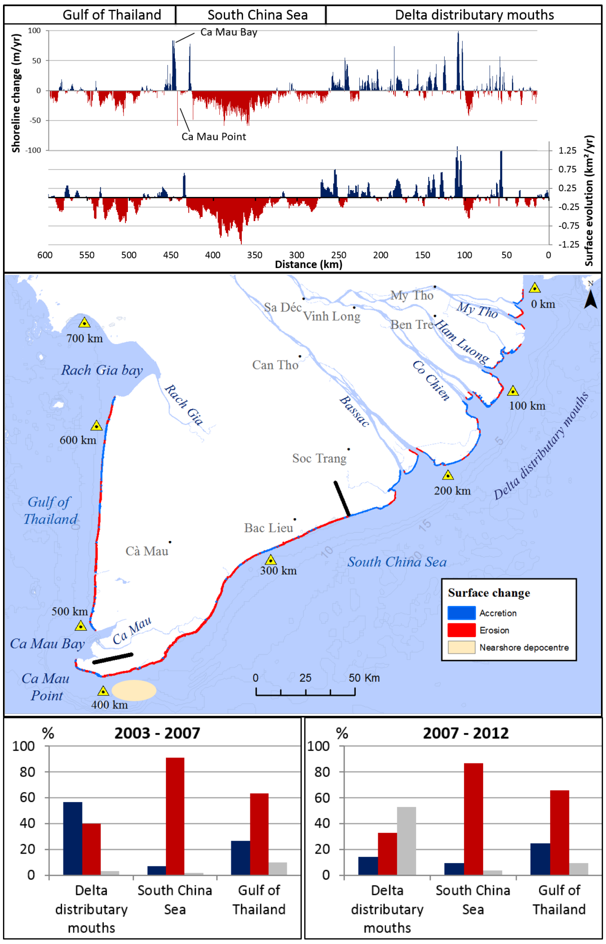

Figure 1. Top: Graphs of shoreline (m/year, error ±0.5 m/yr) and coastal area (km^2/year, error ±0.005 km^2/yr) change rates for the Mekong River delta between 2003 and 2011/12 analysed from high-resolution SPOT 5 satellite images. The map shows shoreline accretion and erosion sectors divided into three sectors: the sand-bound delta distributary mouth (DDM) sector comprising beaches with mildly developed aeolian dunes, the muddy South China Sea (SCS) where past deltaic progradation rates were highest, and the muddy Gulf of Thailand (GT), both colonised by mangroves increasingly replaced by shrimp farms. Erosion rates along the SCS coast increase towards the southwest with distance from the river mouths but probably also as a function of a close-to shore-normal exposure to Pacific Monsoon waves in conjunction with a decreasing tidal range for the most critically eroding southwestern part. Bubble offshore near Ca Mau Point is a schematic representation of nearshore part of the subaqueous delta displaying high sediment accumulation rates.
Bottom: Net recent shoreline changes along the Mekong delta expressed in percentages of advance (dark blue), retreat (red) and stability (which includes the error band, grey) for the three sectors of delta coast. The embayments of Rach Gia and Ca Mau, which act as efficient mud traps, are not included in the calculation of these mean rates aimed at highlighting open-coast shoreline change.

For the coast downdrift of Cabo Orange, we have produced time series of mangrove maps using archival remote sensing images (Walcker et al., in press). We also retrieved significant wave-heights (H_S), mean wave periods (T_M) and mean wave directions (θ_M) from the European Centre for Medium-Range Weather Forecasts reanalysis products, and used complex empirical orthogonal function (CEOF) decomposition to extract the main mode of mangrove surface area (M_S) variability, and singular value decomposition (SVD) to test the relationships between M_S and H_S, T_M and θ_M. We show from these linear statistics that variations in the extent of mangroves are driven by large-scale, low-frequency changes in North Atlantic waves that are related to the NAO. Such a relationship is hypothesized to operate through wave pounding, which alters the mud substrates on which mangroves thrive, and which varies with the phase of the NAO (Fig. 3). In addition to work on mangroves, the morphodynamics of the rare sandy beaches on the Amazon-influenced coast are also being monitored using cutting-edge photogrammetric techniques (Brunier et al., submitted).

3. Shoreline changes in the Ganges-Brahmaputra delta

A remote sensing study of the seaward fringes of the Ganges-Brahmaputra delta shows progradation between 1973 and 2014 (Ricout, Master's Dissertation), with an annual net land gain and a net shoreline advance of 7.05 km²/yr and 0.18 m/yr respectively. Progradation is assured (for about 84.7%) by fluvial-tidal islands abundant in the Meghna estuary (active river mouths, Table 1). The western half of the delta, which includes the mangrove system of the Sundarbans, shows erosion, and appears to be largely disconnected from the river system. Deltaic progradation has declined over time with a turnaround to erosion over the decade 2003-2014 (Fig. 4) that may be linked to dams and embankments. This trend entail future increased vulnerability of the GBM delta to natural hazards such as cyclones, tidal surges and tropical storms, which are highly recurrent in the Bay of Bengal.

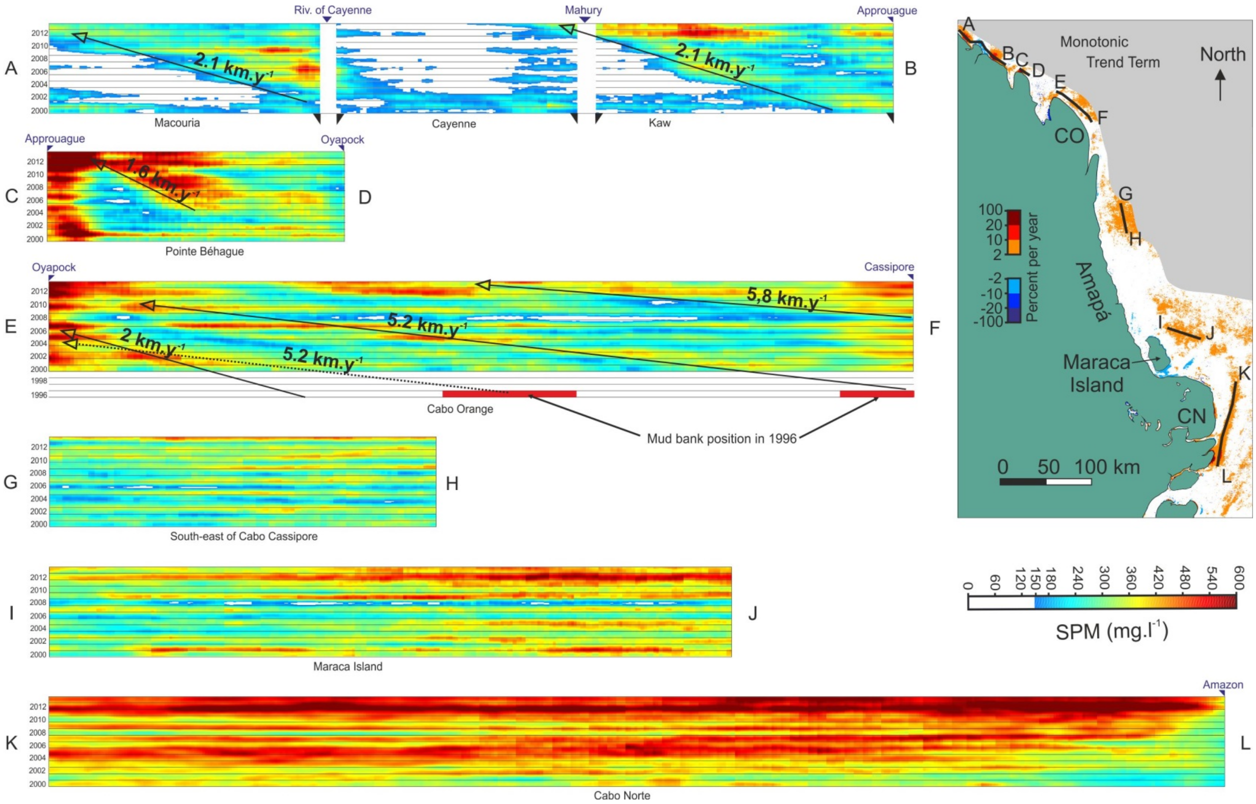

Figure 2. Time-space diagrams of trend cycle SPM concentrations from February 2000 to December 2013 (seasonal and irregular variations are removed) computed over six profiles, A to L, realized in areas of significant monotonic trend. Within the profile along Cabo Orange (E-F), the approximate position of two mud banks described by Allison et al. (2000) is indicated and the dashed arrow indicates the present position of one of these mud banks if its mean migration velocity was approximately of 5.2 $km.y^{-1}$. The map in the upper right corner is a detailed view of the significant monotonic trend term presented in figure 6 with the profile positions (from Gensac et al., in revision).

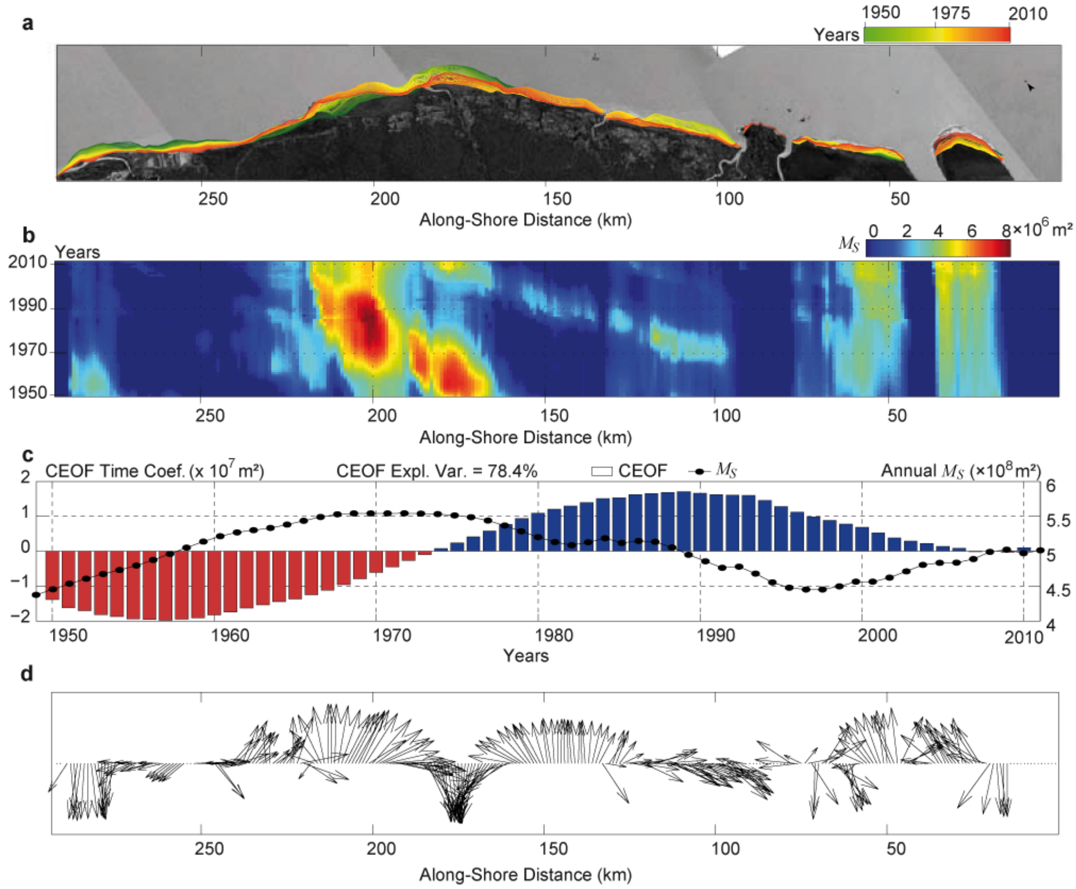

Figure 3. Variations in mangrove surface area (M_S) on the Amazon-influenced coast of French Guiana analyzed in order to capture the leading pattern of variability. (**a**) Map of yearly shoreline positions spanning the period 1950–2010. (**b**) The Hovmöller diagram of M_S shows that time variations are related to propagating features that migrate along-shore from East to West. (**c-d**) Complex Empirical Orthogonal Function (CEOF) analysis used to extract the leading mode of variability. (**c**) Bars indicate the time behaviour of the real part of the CEOF mode and the score of the variance explained (Expl. Var.). The dotted black line indicates the annual M_S budgets and is plotted on the left axis. (**d**) Complex correlations between the time series of the CEOF mode and that of each coastal section. The length of the arrow represents the magnitude of the correlation and the orientation represents the time lag between the two time series. An arrow pointing upwards (downwards) indicates positive (negative) correlation with no lag. One pointing to the left (right) indicates that the coastal section leads (lags) the CEOF mode. From Walcker et al. (accepted).

Table 1. Land gains and losses and shoreline change rates along the 1205 km-long GBM coast between 1973 and 2014 on the basis of 4 sectors.

	Sector 1 Meghna Estuary (active mouths)	Sector 2 Kuakata (intermediate)	Sector 3 Sunderbans (abandoned lobe)	Sector 4 Hoogly Estuary (abandoned lobe)
(km²/yr)	**11.04**	**-0.30**	**-3.19**	**-0.49**
(m/an)	**7.80**	**-5.52**	**-8.43**	**-5.92**

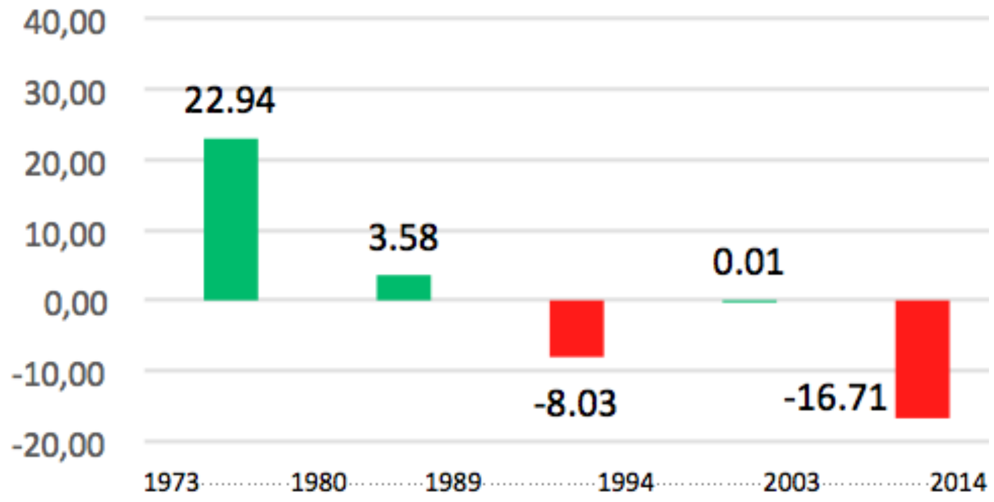

Figure 4. Land area changes along the GBM delta shoreline since 1973. The results show net delta erosion over the decade 2003-2014.

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Publications and unpublished research partly or wholly funded by the Belmont Deltas project

Anthony, E.J., 2015. Wave influence in the construction, shaping and destruction of river deltas: A review. Marine Geology, 361, 53-78.

Anthony, E.J., Almar, R., Aagaard, T. Recent shoreline changes in the Volta River delta, West Africa: the roles of natural processes and human impacts. In press, African Journal of Aquatic Science.

Anthony, E.J., Besset, M., Brunier, G., Goichot, M., Dussouillez, P., Nguyen, V.L.. Linking rapid erosion of the Mekong River delta with human activities. In revision, Scientific Reports.

Gensac., E., Martinez, J.M., Vantrepotte, V., Anthony, E.J. Seasonal and inter-annual dynamics of suspended sediment at the mouth of the Amazon River: The role of continental and oceanic forcing, and implications for coastal geomorphology and mud bank formation. In revision, Continental Shelf Research.

Gratiot, N., Anthony, E.J. The contribution of flocculation and settling processes to the sediment dynamics and geological development of the mangrove-colonized, Amazon-influenced mud-bank coast of South America. Submitted, Marine Geology.

Walcker, R., Anthony, E.J., Cassou, C., Aller, R.C., Gardel, A., Proisy, C., Fromard, F. Control of mangrove abundance by decadal changes in oceanic wave fields. In press, Journal of Biogeography.

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Brunier, G., Fleury, J., Anthony, E.J., Gardel, A., Dussouillez, P. Close-range airborne photogrammetry: an effective tool for high-resolution sandy beach morphometric surveys. Examples from embayed beaches in French Guyana. Geophysical Research Abstracts, Vol. 17, EGU2015-6019, EGU General Assembly 2015, Vienna.

Brunier, G., Anthony, E.J., Gardel, A. Rapid shoreline erosion induced by human impacts in a tropical muddy coast context, an example from western French Guiana. Geophysical Research Abstracts, Vol. 17, EGU2015-6019, EGU General Assembly 2015, Vienna.

Master's Dissertation (Belmont-funded)

A. Ricout, 2015. Evolution du trait de côte du delta du Gange-Brahmapoutre de 1973 et 2014. Abstract in English. Aix-Marseille Univ.

University of Southampton

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

World Conservation Monitoring Centre

Neil Burgess, Marieke Sassen and Arnout van Soesbergen

Research Themes and Accomplishments during 2014-2015

This progress update is divided into eight short sections. These include updates on data collection and analysis, fast track papers, publications, the special issue in Sustainability Science, conference presentations, communication and outreach, analysis of commodity prices and work undertaken by WCMC-UNEP.

1. Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon

Since the beginning of the project the University of Southampton acquired the following datasets: Bangladesh Household Income and Expenditure Survey (HIES) and Vietnamese Household Living Standards Survey (HLSS 1992; 2002; 2012) and the Brazil Consumer Expenditure Surveys (2002-03; 2008-09). In addition, hard copies of the 1989 edition of the Vietnamese census have been purchased. Socio-economic and demographic indicators were collected from a number of reports, including the most recent and previous censuses, sample vital registration system (SVRS), demographic and health surveys (DHS), and maternal mortality surveys (BMMS). Data on historical trends and selected environmental indicators were collected and acquired from a number of sources, including the Mekong River Commission. The main focus areas of the analysis undertaken include: demographic analysis, socio-economic analysis and trends analysis.

<u>Demographic analysis</u>
Demographic (district level) projections have been conducted for the coastal GBD in collaboration with colleagues from the International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b). This work has been published as a working paper with the Centre for Population Change (CPC). Jointly with project partners, a demographic overview across the three delta regions has been undertaken, including the analysis of the population structures and specific components of population change (mortality, fertility, migration) in all study areas. This collaborative work will be published as a working paper with the Centre for Population Change (CPC) and is currently under review in *Sustainability Science*.

<u>Socio-economic analysis</u>
Another key aspect of BF-related work at the University of Southampton involves analysis of household survey data (budget surveys). A number of socio-economic analyses was

conducted to date with a focus on the Ganges Brahmaputra Delta and the Mekong Delta. The specific topics and research questions included:

- What are the associations between soil salinity, household wealth and household food security in south-western Bangladesh?
- What is the extent of inter urban inequalities in the Ganges Brahmaputra Delta?
- What are the determinants and impacts of remittance flows in the Ganges Brahmaputra and Mekong delta regions?
- What are the associations between natural hazards and livelihoods in the Indian Sundarban Delta?

Trend analysis

Jointly with colleagues from the Mekong Delta Development Research Institute (MDDRI), we undertook the analysis of biogeophysical and socio-economic trends in the three study areas. The paper is currently under review in *Sustainability Science*.

Engagement with global policy debates

2015 is a critical year for the deltas for at least two reasons. It is the year of Sustainable Deltas (SD2015) and the year, in which the new development goals (the Sustainable Development Goals, or SDGs) are launched. In this context, we led a policy relevant commentary published in *Environment: Science and Policy for Sustainable Development.* Further policy orientated research output are being discussed.

2. Communication, outreach, knowledge exchange

Since the start of the project a BF_DELTAS Twitter account has been established and regular tweets are being posted. University of Southampton has also created a dedicated space on its website summarising the project and project's objectives. Several blog articles have been posted on the World Bank's website. These include:

Szabo, S. and Matthews, Z. (2015) "How to design an effective SDG indicator framework? ", World Economic Forum, available: https://agenda.weforum.org/2015/08/designing-effective-sdg-indicator-framework/

Szabo, S. (2015) "Deltas Drained: Dealing with population migration in Bangladesh", The World Bank, available: http://blogs.worldbank.org/endpovertyinsouthasia/deltas-drained-dealing-population-migration-bangladesh

Szabo, S. (2015). "Shifting population structures and climate change as key drivers of future migration trends", The World Bank, available: http://blogs.worldbank.org/peoplemove/shifting-population-structures-and-climate-change-key-drivers-future-migration-trends

Szabo, S. (2014). "Is Bangladesh likely to achieve its 2021 universal food security target?", The World Bank, available: http://blogs.worldbank.org/endpovertyinsouthasia/bangladesh-likely-achieve-its-2021-universal-food-security-target

In May/June 2015 the University of Southampton hosted Ms Rituparna Hajra, Research Fellow at the University of Jadavpur. We collaborated on the paper "Natural hazards, livelihoods and sustainable development: evidence from the Indian Sundarban Delta" and are currently conceptualising further planned research outputs.

3. Analysis of commodity prices (consultancy)

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.

4. Work undertaken by WCMC-UNEP

UNEP-WCMC has only recently started to fully engage with the Delta's Belmont Forum project. However, they have recently completed a 3-year project on assessing the impacts of commodities development on biodiversity and ecosystem services in a number of regions (http://www.unep-wcmc.org/featured-projects/commodities-and-biodiversity), including the Mekong basin. This project used stakeholder driven regional socio-economic scenarios and climate change scenarios and sophisticated economic and land use modelling to assess potential future impacts of land use changes on biodiversity and ecosystem services. Whilst not focussing on the Mekong delta specifically, relevant outputs from this project can and will be used in planned work for the Belmont Forum project in collaboration with University of Southampton.

Planned work
Using some of the above described data and methods, as well as further datasets generated within the Belmont Forum Delta's project the following activities will be undertaken:

In collaboration with University of Southampton, prepare two papers:

- Paper 1: Policy relevant paper bringing together analysis and data for all three Delta regions
- Paper 2: a more technical paper using the above described datasets and focusing on the Mekong delta specifically.

Furthermore, UNEP-WCMC is contributing to the development of a joint Belmont Delta's session at the IUCN World Conservation Congress Forum in Hawai'i September 2016. This will provide an excellent forum to present the collaborative papers on Delta's as well as communicate these results to a wider conservation focused audience.

5. Fast track papers

University of Southampton led the following two fast track papers:

FT1: Szabo, S., Brondizio, E., Hetrick, S., Matthews, Z., Renaud, F. G., Nicholls, R. J., Sebesvari, Z., da Costa, S., Dearing, J. S., Foufoula-Georgiou, E. "Population dynamics in the context of environmental vulnerability: Comparison of the Mekong, Ganges Brahmaputra and Amazon delta regions"

FT2: De Araujo Barbosa, C.C., Dearing, J.A , Szabo S., Hossain, M.S., Nhan, D.K., Binh, N.T., Matthews, Z. "Evolutionary social and biogeophysical changes in the Amazon, Ganges-Brahmaputra-Meghna and Mekong deltas"

Our staff are also contributing to the following fast track paper:

FT4: 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"

Publications

Szabo, S., Hajra, R, Baschieri, A., Matthews, Z. (2015) "Inequalities in human well-being in the urban Ganges-Brahmaputra Delta: implications for sustainable development". CPC Working Paper 67, University of Southampton, available: http://www.cpc.ac.uk/publications/cpc_working_papers.php

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

Davis, A., Matthews, Z., Szabo, S and Fogstad, H. (2015) "Measuring the Sustainable Development Goals: a two-track solution", The Lancet, 386, (9990), 221-222.

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Under review

Szabo, S., Brondizio, E., Hetrick, S., Matthews, Z., Renaud, F. G., Nicholls, R. J., Sebesvari, Z., da Costa, S., Dearing, J. S., Foufoula-Georgiou, E. "Population dynamics in the context of environmental vulnerability: Comparison of the Mekong, Ganges Brahmaputra and Amazon delta regions"

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"

Szabo, S., Hossain, S., Matthews, Z., Lazar, A., Ahmad, S. "Soil salinity, household wealth and food insecurity in agriculture-dominated delta" (revise and resubmit)

Szabo, S., Begum, D., Ahmad, S., Matthews, Z., Streatfield, P. K. "Population Projections for Ganges Brahmaputra Delta (2011-2051)" (revise and resubmit)

De Araujo Barbosa, C.C., Dearing, J.A , Szabo S., Hossain, M.S., Nhan, D.K., Binh, N.T., Matthews, Z. "Evolutionary social and biogeophysical changes in the Amazon, Ganges-Brahmaputra-Meghna and Mekong deltas"

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. 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"

Hajra, R., Szabo S., Ghosh, T., Matthews, Z., Foufoula-Georgiou, E. “Natural hazards, livelihoods and sustainable development: evidence from the Indian Sundarban Delta”

Work in progress

Szabo, S. Wisniowski, A., Matthews, Z. “Remittances, food insecurity and gender in Bangladesh”

Szabo, S., Bispo, S., Matthews, Z. (and potentially other colleagues) “recent trends and determinants of human wellbeing the Amazon delta region”

Special issue on delta regions

Jointly with the United Nations University, we are leading on a special issue ‘Sustainable deltas: livelihoods, ecosystem services and policy implications’. This volume is due for publication in *Sustainability Science* in July 2016. Currently, 15 papers are under review.

Conferences

Szabo, S. et al. "Home is where the money goes: determinants and impacts of remittances in the Ganges Brahmaputra and Mekong delta regions”, Asian Population Conference 2015

Szabo, S. et al. " Inequalities in human well-being in the urban Ganges Brahmaputra Delta: A capabilities and human rights approach”, Asian Population Conference 2015

Szabo, S. Wisniowski, A., Matthews, Z. “Remittances, food insecurity and gender in Bangladesh”, paper presented at the 9th Conference on Global Health and Vaccination Research in Oslo, March 2015

Szabo, S. et al. "A tale of two deltas: determinants and impacts of remittances in the Ganges Brahmaputra and Mekong delta regions”, American Population Conference 2015

Szabo et al. “Inequalities in human well-being in the urban Ganges Brahmaputra Delta: A capabilities and human rights approach”, American Population Conference 2015

Szabo, S. et al. “Rural development and food insecurity in the Ganges Brahmaputra Delta: challenges and prospects”, International Conference Deltas in Times of Climate Change II, 24-26 September, Rotterdam

Szabo, S. et al. “Food insecurity in the rural Ganges Brahmaputra Delta: The impact of soil salinity and households’ socio-economic characteristics”, International Risk and Disaster Conference, August 2014, Davos

Special sessions on deltas

American Geophysical Union Annual Conference 2015 (co-convenor, jointly with University of Colorado, United Nations University and University of Texas)

American Geophysical Union Annual Conference 2014 (lead convenor, jointly with UNIVAP)

British Society for Population Studies Conference 2015 (convenor)

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 2014-2015

1. Collation and correction of SRTM topographic data and adjustment to local cartographic and topographic datasets in deltas

The SRTM data from the Gangetic delta have been collected. The collected data were plotted in the GIS maps with 30m resolution to prepare the digital elevation map (DEM) of the study area (Fig. 1) Even though the map is coarser in nature it indicated that most of the Ganges delta is low lying and vulnerable to flooding. However these maps will be corrected at field with RTK GPS survey by validating the land elevation. Additionally the map will be refined with SRTM data. Based on this topographic map the vulnerable areas along the delta will be classified through extensive field verification.

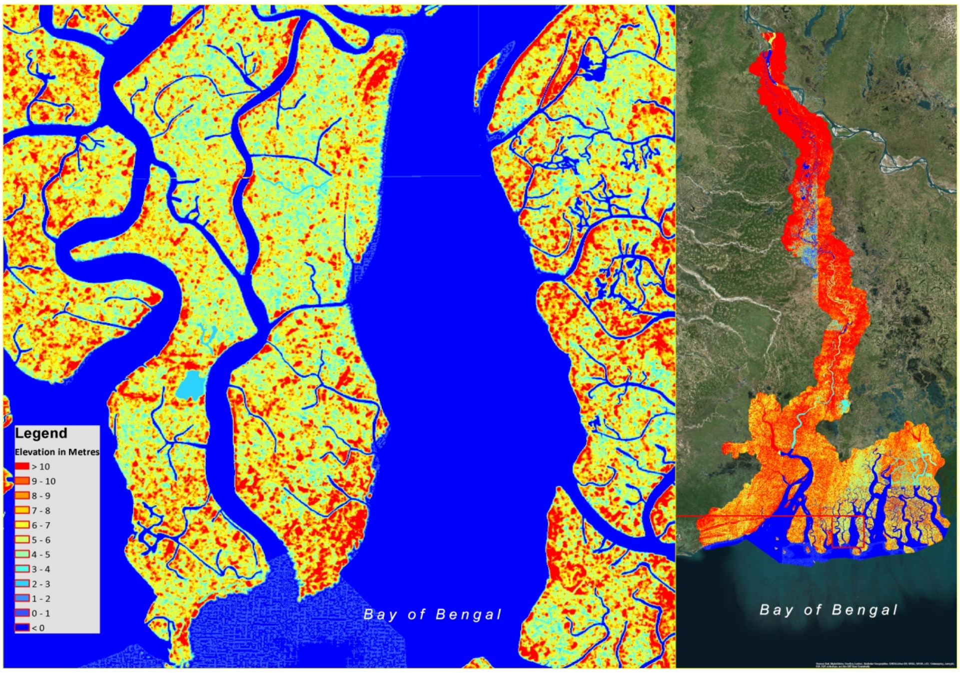

Figure 1. Digital elevation map for the Hooghly River (5 km either side of Hooghly River)

2. Collection of census data for economic, social, and demographic variables and association to geospatial data platforms for deltas

The first part of the study focuses on the socio-demographic changes in the core delta region of West Bengal in 9 delta districts. The first part presents a desk-based review of basic socio-demographic parameters related with the delta region. The parameters include, among others, population, density, literacy rates, occupational changes and its impact on state gross domestic product, infrastructure facilities such as electricity and access to water. The collected data were put in GIS platform to understand the trends and pattern in the variability. The second part of the study focuses on the socioeconomic impact of land-use/land-cover changes and the third part focuses on the development of a master plan to maximise the ecological-economic benefits to the region. The main targets for this study are:

a) To delineate the socio-demographic changes in the Ganges delta region.

b) To identify the land-use/land-cover changes dude to anthropogenic factors

c) To identify the ecological-economic factors leading to degradation of Ganges delta region.

d) To incorporate variability in GIS based platform for understanding the trends and pattern in the viability of the data set.

3. Assimilation of data on flooding and sediment aggradation; habitat modification; climate change effects; demographics and socio-economics

- Population in the region bordering Ganges delta in West Bengal has increased by over 140 million over the last 2 decades. Kolkata's urban agglomeration accounted for an increase of over a million people in the last decade alone.
- Data on flooding and sediment aggradations were assimilated; Landuse–landcover map was prepared for 5 km on either side of the Hooghly River from Farakka Barrage to Kolkata and from Kolkata to entire southern part of West Bengal (including Indian Sundarban – covering 10 districts).
- The increase in literacy level has not resulted in decline in the proportion of non-workers and agricultural labourers during the period.
- The small and marginal farming possibly have become uneconomical and many of them have been forced to sell their land but still continue to work as agricultural labourers. Production of oil seeds has seen phenomenal growth.
- Yield rates in the delta have displayed a positive trend over the last 30 years. Improved irrigational technologies and fertilizer use have contributed to 2 % CAGR the state agriculture and overall improvements in yield rates.

4. Map ecosystem dynamics (derivation from satellite imagery - mangrove decline, coastline changes, and urban sprawl)

Applying remote sensing and GIS techniques on the multi-temporal satellite image and topo-sheets, shoreline extraction using water index and subsequent change detection analysis have been carried out to assess the erosion-accretion pattern in the region. The shoreline in the deltaic region of West Bengal has never been constant and shows a continuous changing pattern. Both the spatial and temporal variations in the deposition and accretion have been observed in the study. Shoreline changes along the Hooghly, Matla and other rivers of Ganges delta is depicted in figure 2.

However, the erosion and accretion patterns clearly show a continuous geomorphic sculpturing over the coastal tract. Erosion works as a constant factor for the coastline modification in the most of the areas some places has also showed deposition processes (Pichchabani). The coastline shows a gradual shift towards adjacent land as a consequence mainly of wave erosion.

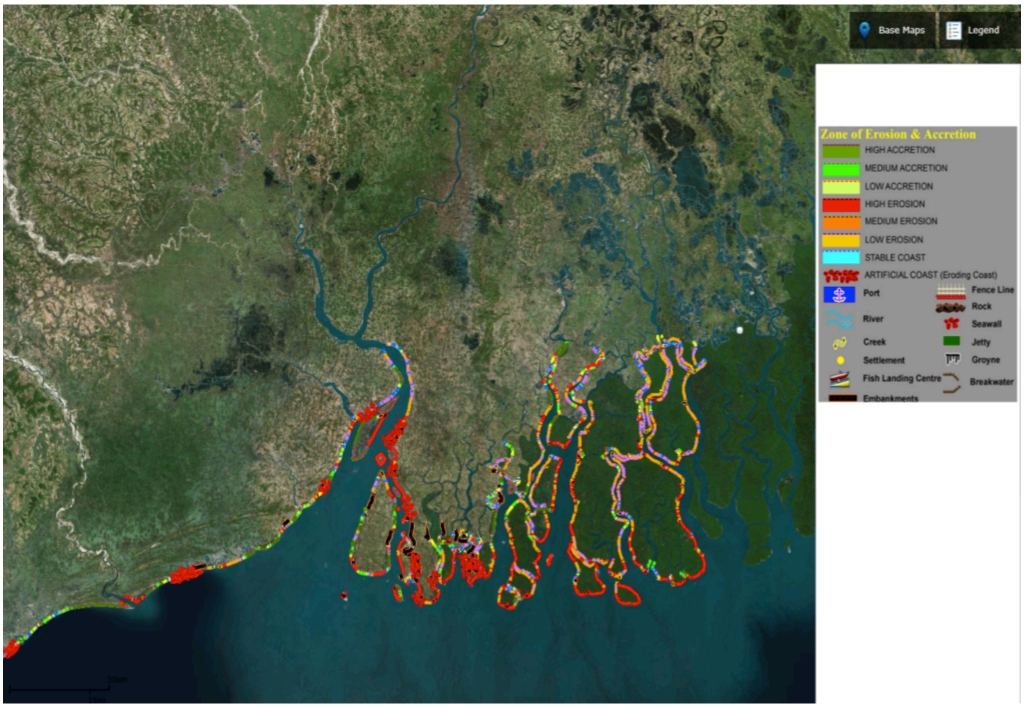

Figure 2. Shoreline changes along the Hooghly, Matla and other rivers of Ganges delta.

The rise in sea level and availability of less fresh water particularly during winter when rainfall will be less will cause inland intrusion of saline water. As a result, many mangrove species, intolerant of increased salinity, may be threatened. In addition, the highly dense human settlements just outside the mangrove area will restrict the migration of the mangrove areas to less saline area. The shrinking of the mangrove areas will have effect on the country's economy.Change in mangrove forest cover Sundarban is shown in Figure 3.

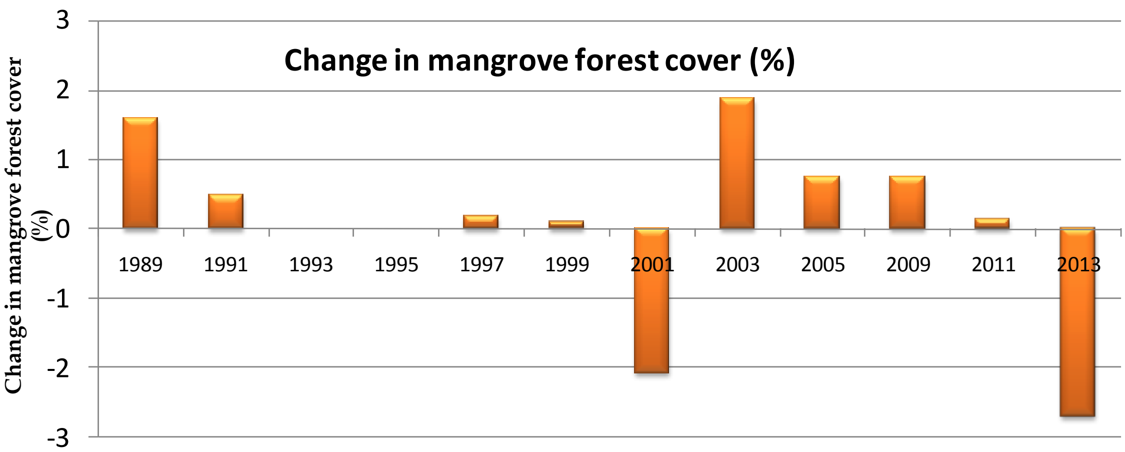

Figure 3. Change inSundarban mangrove forest cover (FSI, 2013 and ISRO, 2015)

5. The bio-physical, ecological, geomorphology, and climate data from the Gangetic delta region collected and compiled in a IT-enabled GIS modelling platform

- The bio-physical, ecological, geomorphology and climate data from the Gangetic delta region have been collected and compiled in an IT-enabled GIS modelling platform.
- Biogeochemical modelling (Land-Ocean Interactions in the Coastal Zone - LOICZ) of water, salt and nutrient distribution in the Hooghly River was carried out. The seasonal rates of Net Ecosystem Metabolism (p-r) of the estuary were negative [(p – r) is (-) 0.58 and (-) 0.25 mmol C m^{-2} d^{-1} in the wet and dry seasons respectively)], which indicated persistent heterotrophy in the estuary.
- Net anthropogenic nitrogen input (NANI) budget for Ganges watershed was prepared.Overall Ganges showed high NANI value, driven mainly by high agricultural fertilizer inputs which in turn dominate the anthropogenic nitrogen inputs in Ganges basin. Ganges basin is a net importer of N in food/feed due to the demand of its large human and livestock density, in spite of intensive agricultural production in this region.

Future Work plan (2015-2016)

In the coming year 2015-16, the following tasks shall be carried out for the Ganges Deltaic research study.

S. No	Ongoing Tasks	Nature of the work
1	Ground validation of the collected dataset	GIS based/ Field survey
2	River discharge estimations will be carried out various river locations at *Hooghly River*.	Experimental/ Field based
3	Bathymetric survey will be carried out selected locations at Hooghly River	Experimental/ Field based
4	Collection of long term time series water quality and metrological data using real time data buoy monitoring system and *automatic weather station* (AWS) will be established.	Experimental/ Field based
5	Effect of the river and tidal flow rate for sediment transportation in the Hooghly river	Experimental/ Field based
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	GIS based/ Field survey
8	Collection and harmoinaztion of the missing data in socioeconomic and environmental sectors (Primary and secondary based)	GIS based/ Field survey
9	Contribute to prepare the Global Delta Vulnerability Index for Ganges Delta, India.	Analytical
10	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.

Yoshiki Saito
National Institute of Advanced Industrial Science and Technology, acting through Geological Survey of Japan

Akiko Tanaka, Toru Tamura, Yutaka Kanai, Kan-His Hsiung (GSJ, AIST), Kastuto Uehara (Kyushu University), Kazuaki Hori (Nagoya University)

Research Themes and Accomplishments during 2014-2015

To understand system functioning in deltas is a basis for the evaluation of present status, human impacts, and sustainability of deltas. The knowledge of system functioning in deltas naturally is crucially important for sustainable management of deltas. To discriminate natural and anthropogenic changes recognized at present, system functioning on long time-scales is also important. For better understanding of present delta degradation and anthropogenic impacts, GSJ group has foci on decadal to millennial time-scales morpho-dynamics and present sediment- and morpho-dynamics of the Mekong River delta.

1. Field expeditions

Yoshiki Saito had field expeditions in river channels of the Mekong River delta in Vietnam during dry season in January, February, March and May 2015 as collaborative research with Ho Chi Minh City Institute of Resources Geography, Vietnam Academy of Science and Technology (Dr. Nguyen Van Lap & Ta Thi Kim Oanh). In total ~210 channel-bottom sediments were taken from the whole Mekong River delta in Vietnam from the border of Cambodia to five river mouths. The sediments in river channels are divided into mainly three groups by sedimentary facies: river-dominated, tide-dominated and marine-dominated sediments. Their distributions are spatially different and closely related to river morphology. This will be the first systematic survey of sediments in river channels for the whole Mekong River delta in Vietnam. Preliminary result will be presented at the delta session at 2015 AGU fall meeting, December 2015.

Figure 1. Sampling locations of sediment in river channels of the Mekong River delta.

2. Long-term morphodynamics

Shoreline erosion is one of crucially important topics of the Mekong River delta recently from viewpoints of environmental conservation and delta sustainability. Long-term shoreline migration of the Mekong River delta was detected by morphological and chronological analyses using OSL dating for a series of beach ridges developing in the central parts of the Mekong River delta (Tamura et al., 2012, 2013). This method has been applied widely to the Mekong River delta using newly collected samples. We reconstructed the long-term shoreline changes of the Mekong delta over the last 2500 years based on the architecture and chronology of beach ridges on delta plains in Ben Tre and Tra Vinh to consider the sediment flux and its contribution to the growth of individual delta plains. While each delta plain shows temporal changes in growth rate, the sum of these plains is nearly constant for the last 2500 years. This result indicates that the present coastal erosion of the Mekong River delta (shown by Anthony and others) is an unprecedented phenomenon. This result will be presented at the delta session at 2015 AGU fall meeting, December 2015 and at GSA annual meeting in November 2015 by Toru Tamura and others.

3. Special session organization

Yoshiki Saito was a convener of the session: "Impacts of Global Change on Deltas and Coastal Wetland Ecosystems: Scientific Advances in Support of Socioecological Resilience II", AGU Fall Meeting, 15-19 Dec 2015, San Francisco, CA, USA. Yoshiki Saito was a convener of the session: "DELTAS: Evolution,

Morphodynamics, Human Impacts, and Sustainability", XIX International Union for Quaternary Research (INQUA) Congress, 26 July to 2 August 2015, Nagoya, Japan with 21 oral and 12 poster presentations. Yoshiki Saito is a convener of the session: "Delta, coast and estuarine systems", 8th International Conference on Asian Marine Geology (ICAMG-8) to be held on 5-10 October 2015, Jeju, Korea. 33 abstracts were submissions (24 orals and 9 posters).

4. Team meeting participation

Yoshiki Saito participated in BF-DELTAs team meetings in the AGU fall meeting, San Francisco, CA, USA in December 2014 and in "Deltas in Times of Climate Change II" meeting in Rotterdam, Netherlands in September 2014.

Publications (partially funded by this grant)

Tjallingii, R., Stattegger, K., Stocchi, P., Saito, Y., Wetzel, A., 2014. Rapid flooding of the southern Vietnam shelf during the early to mid-Holocene. Journal of Quaternary Science, vol. 29, no. 6, pp. 581–588.

Parham, P., Saito, Y., Sapon, N., Suriadi, R., Mohtar, N.A., 2014. Evidence for ca. 7 ka maximum Holocene transgression on the Peninsular Malaysia East coast. Journal of Quaternary Science, vol. 29, no. 5, pp. 414–422.

Zhou, L.Y., Liu, J., Saito, Y., Zhang, Z.X., Chu, H.X., Hu, G., 2014. Coastal erosion as a major sediment supplier to continental shelves: example from the abandoned Old Huanghe (Yellow River) delta. Continental Shelf Research, vol. 82, pp. 43–59.

Saito, Y., 2014. Very thick muddy successions preserved in East and Southeast Asian coastal zones since the last glacial maximum. Proceedings of International Workshop on Quaternary shelf mud: Processes, Facies and Stratigraphy, At Daejeon, Korea, 1–4 September 2014, KIGAM, pp. 40–44.

Wu, X., Bi, N.S., Kanai, Y., Saito, Y., Zhang, Y., Yang, Z.S., Fan, D.J., Wang, H.J., 2015. Sedimentary records off the modern Huanghe (Yellow River) delta and their response to deltaic river channel shifts over the last 200 years. Journal of Asian Earth Sciences, vol. 108, p. 68–80.

Qiu, J.D., Liu, J., Saito, Y., Yang, Z.G., Yue, B.J., Wang, H., Kong, X.H., 2014. Sedimentary evolution of the Holocene subaqueous clinoform off the southern Shandong Peninsula in the western South Yellow Sea. Journal of Ocean University of China, vol. 13, pp. 747–760.

Zhou, L.Y., Liu, J., Saito, Y., Liu, J.P., Li, G.X., Liu, Q.S., Gao, M.S., Qiu, J.D., 2014. Fluvial system development and subsequent marine transgression in Yellow River (Huanghe) delta and its adjacent sea regions during Last Glacial Maximum to early Holocene. Continental Shelf Research, vol. 90, pp. 117–132.

Suthisanonth, R., Jarupongsakul, T., Saito, Y., Kanai, Y., Nishimura, K., 2015. Evaluating seafloor erosion by side-scan sonar survey in muddy coast of Chao Phraya River Mouth, Thailand. Conference Proceedings of ACENS & ICCEE, February 2015, Tokyo, pp. 498–507.

Tanaka, A., Uehara, K., Tamura, T., Saito, Y., Nguyen, V.L., Ta, T.K.O., in press. Temporal changes in river-mouth bars from L-band SAR images: a case study in the Mekong River delta, IAS Special Publications.

Presentations (partially funded by this grant)

Tamura, T., Recent progress in studies of beach ridges as palaeoenvironment records. AOGS 11th Annual meeting, 2014, July, Sapporo, Japan.

Saito, Y. Deltas in Asia: Holocene evolution and Anthropocene collapse. AOGS 11th Annual meeting, 2014, July, Sapporo, Japan. [Invited]

Saito, Y., Nearshore erosional surface in a wave-dominated delta system: example from Holocene Godavari delta, India. William Smith Meeting 2014, September 2014, London.
Saito, Y., Sustainable Deltas 2015. Annual Meeting of Japan Association for Quaternary Research, September 2014, Kashiwa, Japan [Invited]

Saito, Y., Deciphering sediments and morphology: study on Holocene strata and modern processes. 121st Annual meeting of the Geological Society of Japan, September 2014, Kagoshima, Japan [Invited]

Saito, Y., Very thick muddy successions preserved in East and Southeast Asian coastal zones since the last glacial maximum. International Workshop on Quaternary shelf mud: Processes, Facies and Stratigraphy, 1–4 September 2014, Daejeon, Korea [Invited keynote]

Zhou, L.Y., Liu, J., Saito, Y., Gao, M.S., Qiu, S.B., Pei, S.F., 137Cs and 210Pb dating of recent sediments from a dynamic delta front clinoform: an example from the Huanghe (Yellow River) delta. International Workshop on Quaternary shelf mud: Processes, Facies and Stratigraphy, 1–4 September 2014, Daejeon, Korea [Invited]

Wang, H.J., Bi, N.S, Saito, Y., Wu, X., Wang, A.M., Deltaic responses to dam regulation on river system: Example of the Yellow River, China. 2014 AGU Fall Meeting, 2014/12/16, San Francisco, USA [Invited]

Tanaka, A., Coastal Monitoring Using L-band Synthetic Aperture Radar (SAR) Image Data - Some Case Studies in Asian Delta Areas, 2014 AGU Fall Meeting, 2014/12/16, San Francisco, USA

Hsiung, K.-S, Saito, Y., Sediment supply and sediment storage in deltas of small mountainous rivers since 7 ka, west and southwest Taiwan. 2014 AGU Fall Meeting, 2014/12/16, San Francisco, USA

Suthisanonth, R., Jarupongsakul, T., Saito, Y., Kanai, Y., Nishimura, K., 2015. Evaluating seafloor erosion by side-scan sonar survey in muddy coast of Chao Phraya River Mouth, Thailand. ACENS & ICCEE Joint International Conference, February 2015, Tokyo

Saito, Y., Postglacial sea-level changes, Holocene delta evolution, and Anthropocene changes. DelSEA-III Kick-off meeting, March 2015, Busan, Korea.

Saito, Y., Deltas: Morphology, sediments and processes. 2015 Annual meeting of the Sedimentological Society of Japan, March 2015, Tsukuba, Japan [Invited keynote]

Saito, Y., Holocene delta evolution: A review from deltas in Asia. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Naga Kumar K.Ch.V., Saito, Y., Kubo, S., Nageswara Rao, K., Demudu, G., Rajawat, A.S., Holocene evolution of the Krishna delta, India inferred from sediment facies and AMS 14C ages. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Nguyen, V.L., Ta, T.K.O., Saito, Y., Mekong River Delta: Coastal landform in the last 3000 years and present situation. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Qiao, S.Q., Shi, S.F., Yao, Z.Q., Saito, Y., Holocene sedimentary record of environmental change response to the Huanghe (Yellow River) channel shifts. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Liu, J., Lu, J.F., Qiu, J.D., Saito, Y., Sedimentary evolutions during the last 1.9 Ma in the northern Yellow River Delta coast. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Ta, T.K.O., Nguyen, V.L., Saito, Y., Morpho-sedimentary evolution of the Mekong River Delta, Vietnam during the Holocene. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Hsiung, K.-H., Saito, Y., Sediment storage in deltas fed by small mountainous rivers in terms of source-to-sink: A case study in west and southwest Taiwan. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Zhou, L.Y., Liu, J., Saito, Y., Gao, M.S., Diao, S.B., Qiu, J.D., Pei, S.F., Modern sediment accumulation and sedimentary structure of the modern Yellow River delta. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Song, B., Li, Z., Lu, H.Y., Mao, L.M., Saito, Y., Li, Z., Lu, A.Q., Sha, L.B., Yi, S.H., Zhou, R., Mid-Holocene centennial-decadal climate changes recorded in the Changjiang (Yangtze River) delta plain. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Nageswara Rao, K., Saito, Y., Kubo, S., Naga Kumar, K.Ch.V., Demudu, G., Rajawat, A.S., Palaeogeography and evolution of the Godavari delta, east coast of India during the Holocene: An example of wave-dominated and fan-delta settings. XIX International Union for Quaternary Research (INQUA) Congress, July 2015, Nagoya, Japan.

Tanaka, A., SAR (Synthetic Aperture Radar) data for coastal monitoring in Asian delta areas. XIX International Union for Quaternary Research (INQUA) Congress, 2015/7/31, Nagoya, Japan.

5. Other Accomplishments

ICSU Sustainable Deltas 2015 (SD2015) Initiative: The goals of the SD2015 initiative are to: (1) Increase awareness and attention to the value and vulnerability of deltas worldwide; (2) Promote and enhance international and regional cooperation and data sharing at the scientific, policy, and stakeholder level; and (3) Launch a longer-term effort committed to understanding these complex socio-ecological systems as the cornerstone of ensuring preparedness in protecting and restoring them in a rapidly changing environment. The BF-DELTAS project in collaboration with other delta teams (e.g., Delta Alliance, Delta Dynamics Collaboratory, PIRES, ESPA project) and local stakeholders are promoting the use of research, modeling, and data for management decisions.

Stakeholder workshops on the Amazon delta on May 12-13, 2015 in Belém, Para, Brazil: The United Nations University team members (PI Fabrice Renaud and Zita Sebesvari) of the BF-DELTAS project are initiating stakeholder workshops at the three case study sites, to assess how the Global Delta Vulnerability Index (GDVI) can be designed to be most useful for managers and decisions makers in these regions. The first of these workshops, focused on the Mekong delta, was held on April 2-3, 2014 in Ho Chi Minh City, Vietnam, in collaboration with local BF-DELTAS partners HCMC Institute of Resources Geography, and Vietnam Academy of Science and Technology (VAST). The second of these workshops focused on the Amazon delta held on May 12-13, 2015 in Belém, Para, Brazil, in collaboration with BF-DELTAS partner Indiana University at Bloomington (PI Eduardo Brondizio and Nathan Vogt) and local universities: Museu Paraense Emilio Goeldi, Universidade Federal do Pará and Universidad de Cádiz. The stakeholders' meeting was well attended with 33 registered participants.

Science on a Sphere (SOS): PI Irina 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.

Special sessions at major meetings: The BF-DELTAS project conducted workshops and events at the Rotterdam International Conference 2014, Deltas in Times of Climate Change II (24-26 September 2014): A special Deltas-in-Depth session on "Sustainable Deltas 2015" and a Deltas-in-Practice science-stakeholder workshop on the Mekong delta with stakeholder participants from deltas worldwide. Special sessions for AGU 2015 and EGU 2016 are planned right now.

PI exchanges and Web collaboration ideas: PI Efi Foufoula-Georgiou visited University of Southampton in Aug 2014 to collaborate with Profs. John Dearing and Robert Nicholls on depositional systems. Foufoula-Georgiou presented at the AGU 2014, EGU 2015 and Deltas in Times of Climate Change II International Conference 2014 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.

Special Issue in Sustainability Science: A special issue on the journal *Sustainability Science*: "Sustainable Deltas: Livelihoods, Ecosystem Services and Policy Implications" is lead by PIs Zoe Matthews, Robert J. Nicholls, and Sylvia Szabo. The BF-DELTAS team will submit research papers to this special issue.

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) Several news pieces have appeared around the world (for example in the LOICZ newsletter) about the BF-DELTAS project.
(3) The stakeholder meetings provide a mechanism for transferring the research results to applications. The Deltas-in-practice workshop in the 2014 "Deltas in times of Climate Change II" meeting is one such example.
(4) To take advantage of the popularity and accessibility of social networks, we have launched Twitter and Facebook accounts to disseminate news and information to the public.
(5) PI Sylvia Szabo published a blog entry "Deltas Drained: Dealing with population migration in Bangladesh" in the World Bank Blog *End of Poverty In South Asia* as part of the Global Sustainable Delta Initiative SD2015 (http://blogs.worldbank.org/endpovertyinsouthasia/deltas-drained-dealing-population-migration-bangladesh)

(6) PIs from the BF-Deltas team organized special sessions in various international conferences:

a. PI Irina Overeem was convener of session "Floodplain Dynamics Through Space and Time", AGU Fall Meeting, 15-19 Dec 2015, San Francisco, CA, USA.
b. PI Sylvia Szabo was convener of the session "Livelihoods and Ecosystem Services in Vulnerable Delta Regions: Implications for Policy and Practice", AGU Fall Meeting, 15-19 Dec 2015, San Francisco, CA, USA.
c. Postdoc Zach Tessler was convener of the session: "Impacts of Global Change on Deltas and Coastal Wetland Ecosystems: Scientific Advances in Support of Socioecological Resilience II", AGU Fall Meeting, 15-19 Dec 2015, San Francisco, CA, USA.
d. PI Tom Bucx was organizer of the session "Pathways for adaptation to an uncertain future", Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September 2014.
e. PIs Foufoula – Georgiou and Ramesh Ramachandran were panelists in the session "Deltas and estuaries in peril: towards a global "Community of Practice" on the ecosystem-based-management of deltas under global and climate change", Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September 2014.
f. PI Foufoula – Georgiou was a panelist in the session "Resilient adaptation: how to practice what is preached", Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September 2014.
g. PI Foufoula – Georgiou was convener of the session "Great Debate on Global Freshwater User – The thirsty 10 billion: Are we managing?", EGU General Assembly, 12-17 April 2015, Vienna, Austria.
h. PIs Yoshiki Saito, Edward Anthony and Steven Goodbred Jr. are conveners of the session: "DELTAS: Evolution, Morphodynamics, Human Impacts, and Sustainability" in the XIX INQUA, to be held on July 27 - August 2, 2015, Nagoya, Japan.
i. PI Szabo is organizing a session: "Population dynamics and human well-being in environmentally vulnerable delta regions" in the British Society for Population Studies (BSPS) Annual Conference on September 7 - 9, 2015, University of Leeds.

Mechanisms for Management, Reporting, and Progress Monitoring

Strategic Implementation Plan
In our original proposal we suggested the development of a Strategic Implementation Plan to delineate the expected outcomes of the project. Following our Year 1 project meeting in San Francisco (see below) we decided that the Table of *Milestones and Timetable of Deliverables* in the management Plan of our Belmont Forum proposal (see above) together with an Annual Progress Report and the established Fast Track Papers (FTPs) provided a comprehensive overview of our activities that allow to communicate, integrate, and assess progress throughout the project. In addition the whole group routinely attends regularly scheduled project webinars, and we have used these opportunities to report new results and review progress.

Executive Committee (EC)
Our Belmont Forum proposal stated that we would form an EC to meet quarterly to discuss project progress. This EC has been established and consists of: Efi Foufoula-Georgiou, John Dearing, Zoe Matthews, Steven Goodbred, Zach Tessler, Irina Overeem, Eduardo Brondizio, Yoshiki Saito, and Ian Harrison. The EC consists of a diverse group of scientists in terms of discipline, countries, expertise, and stage of their careers. The EC meets at the annual meetings in person and via telephone 3-4 times per year.

External Advisory Board (EAB)
In the original proposal we discussed forming an EAB comprising of approximately five international experts to meet annually and provide high-level overview of the DELTAS project as well as networking with other international activities on deltas. The EAB is currently under formation and invitations have been extended to a few individuals.

Annual All-hands Meeting
Two major meetings too place during the first year of the grant, to provide for more detailed discussions of project development. The first of these was held at the American Geophysical Union meetings in San Francisco in December in 2013; the second of these will be held at the Deltas in Times Climate Change in Rotterdam in September 2014. The BF-DELTAS team will also be involved in sixteen different sessions/workshop at the Rotterdam conference and will host a side event on "*Sustainable Deltas 2015*" as well as a *"Deltas in Practice"* special session.

Cross-disciplinary cyber-meetings
Overall project management has been achieved by online webinars, scheduled on average once a month, to review progress, identify priority upcoming tasks, and for team members to give presentations about their work. Project files and presentations are uploaded to the project's DropBox for access to all project members. Project communication between cyber-meetings is achieved via an all-group Gmail and via Gmail subgroups specific to tasks.

Stakeholder group
In the original proposal we discussed forming a stakeholder group as part of the Executive Committee. While we might not develop a stakeholder group as a formal part of the EC (since this may be too difficult for arranging meetings with adequate representation) we do intend to ensure that we have strong stakeholder input to the project (eg. see the description of the stakeholder workshops being developed by the United Nations University(Integrated

Work Package 4). We intend to ensure strong stakeholder participation in our sessions at the *Deltas in Times of Climate Change II* Conference in Rotterdam in September 2014.

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. Goodbred Jr, S. L. and C.A. Wilson "Construction and Maintenance of the Ganges-Brahmaputra-Meghna Delta: Linking Process, Morphology, and Stratigraphy", February 2015.
b. Ramachandran, R., "DELTA: Catalyzing action towards sustainability of deltaic systems with an integrated modeling framework for risk assessment", April 2015.
c. Higgins, S. and I. Overeem, "A WMT service component for HydroTrend: simulating sediment transport in large river deltas", April 2015.
d. Overeem, I., A. Kettner, L. Borkowski, B. Russell, H. Peddicord, "Science on a Sphere: Deltas", April 2015.
e. Tessler, Z. and C. Vorosmarty, "Global Environmental Change and Delta Risk", May 2015.
f. Nicholls, R. "Assessing health, livelihoods, ecosystem services and poverty alleviation in populous deltas", May 2015.
g. Mack, B. and C. Kuenzer, "The Potential of Earth Observation for the Monitoring of River Deltas", June 2015.
h. Szabo, S. Determinants and impacts of remittance flows in the Ganges Brahmaputra and Mekong delta regions", June 2015.

(3) Participation of students and postdocs in the Summer Institute on Earth surface Dynamics (SIESD), which in 2015 is on self-organization in landscapes with focus on linking complex surface systems and their depositional records. PIs Efi Foufoula-Georgiou, Irina Overeem and Postdoc Carol Wilson will give lectures on deltas.

(4) Participation of students and post-docs at the AGU 2014, EGU 2015 and CSDMS 2015 meetings where the BF-DELTAS partners meet.

In 2016, we will plan the following major activities:

(1) Plan a high-level science to policy meeting in the United Nations (UN) headquarters in New York City tentatively scheduled around Oct.-Nov. 2015. Preliminary work on its agenda and invitees is in place.

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

(3) 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.

(4) 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.

(5) 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).
(6) Organize 1-2 stockholders meeting in the Ganges Brahmaputra Meghna (GBM), Mekong and Amazon river deltas.
(7) Conduct an all PIs meeting at the AGU 2015.
(8) Research plans for next year are listed by each PI in their own reports submitted to NSF and for PI Foufoula-Georgiou in the attached pdf file which provides plan details on the two major research themes of (a) improved satellite rainfall retrieval over coastal zones, and (b) delta channel network topology and dynamics for delta comparison, physical inference and vulnerability assessment.

6. Affiliated Projects

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 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 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.

NCSCM NATIONAL CENTRE FOR SUSTAINABLE COASTAL MANAGEMENT
Ministry of Environment and Forests, Government of India

National Science Foundation: Award # 0968354   Project duration: 2010-2015

National Center For Sustainable Coastal Management (http://www.ncscm.org/)

(**Ramesh**)

National Centre for Sustainable Coastal Management (NCSCM) is an autonomous centre of the Ministry of Environment and Forests, Government of India, aiming to be a world-class institution for coastal and marine area management. The Centre is established within the Anna University Campus, Chennai. Fourteen institutions have formed a consortium with NCSCM, with Anna University Chennai as the Hub.

Vision

"Promote sustainable coasts through increased partnerships, conservation practices, scientific research and knowledge management for the benefit and well being of current and future generations".

Mission and Role

Support integrated management of coastal and marine environment for livelihood security, sustainable development and hazard risk management by enhancing

- Knowledge
- Research and Advisory Support
- Partnerships and Network
- Coastal Community Interface

Objectives

- Strive to become and remain a World Class knowledge institution pertaining to understanding coastal zones and coastal processes, and pertaining to integrated planning and management of coastal and marine areas.
- Promote integrated and sustainable management of the coastal and marine areas in India for the benefit and well being of the traditional coastal and island communities.
- Advise the Union and State Governments and other associated stakeholder(s) on policy and scientific matters related to ICZM.