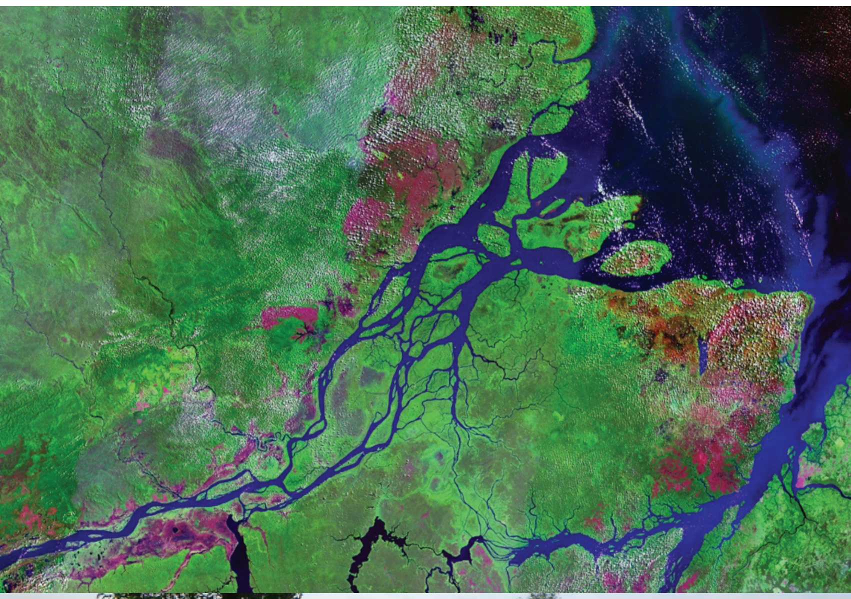
DELTAS
SUSTAINABLE DELTAS 2015

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



BELMONT FORUM

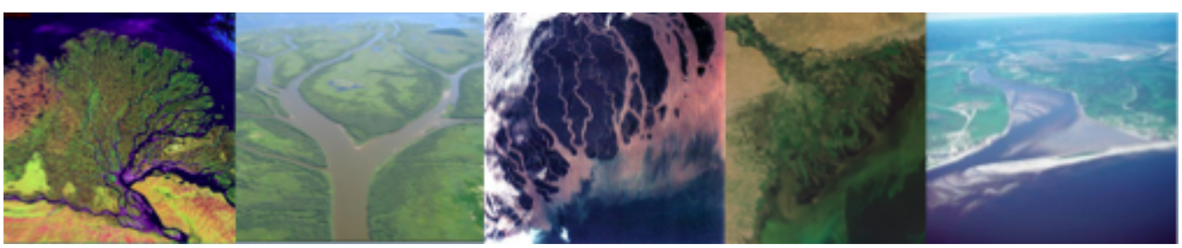
Belmont Forum-G8 Collaborative Research:

BF-DELTAS:

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

Award Number: 1342944

Year 1 Progress Report: 2013–2014



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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.

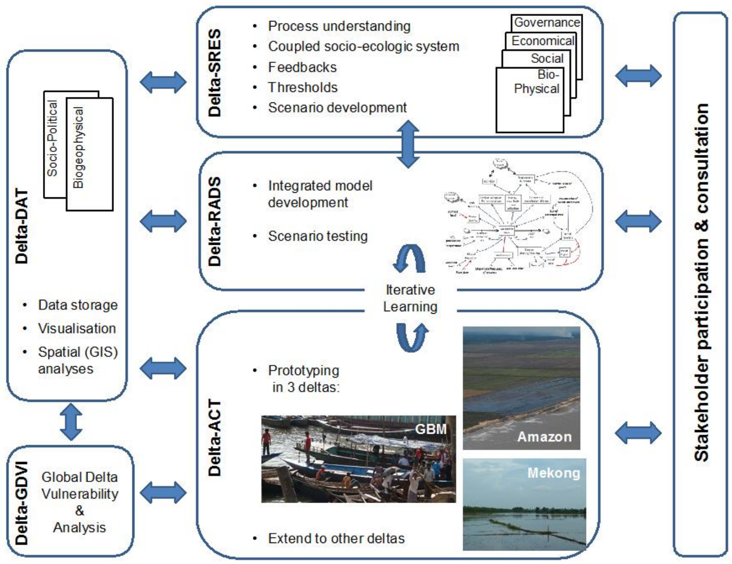
- **Delta-DAT:** *Consolidate data on bio-physical, social, and economic parameters into an international repository of integrated data sets and make these readily available relevant data* for use by the community at large to assess critical parameters, compute vulnerability metrics, and provide input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

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 - Boulder); S. Goodbred Jr. and C. Wilson (Vanderbilt University); I. Harrison (Conservation International); C. Vorosmarty and Z. Tessler (City College of New York); E. Brondizio (Indiana University)

Japan: Y. Saito (Geological Survey of Japan); A. Tanaka (The National Institute of Advanced Industrial Science and Technology)

Germany: C. Kuenzer (German Aerospace Center); F. Renaud and Z. Sebesvari (United Nations University)

France: E. Anthony (Aix-Marseille University)

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 (UNEP - World Conservation Monitoring Centre)

India: R. Ramesh (Anna University)

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

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

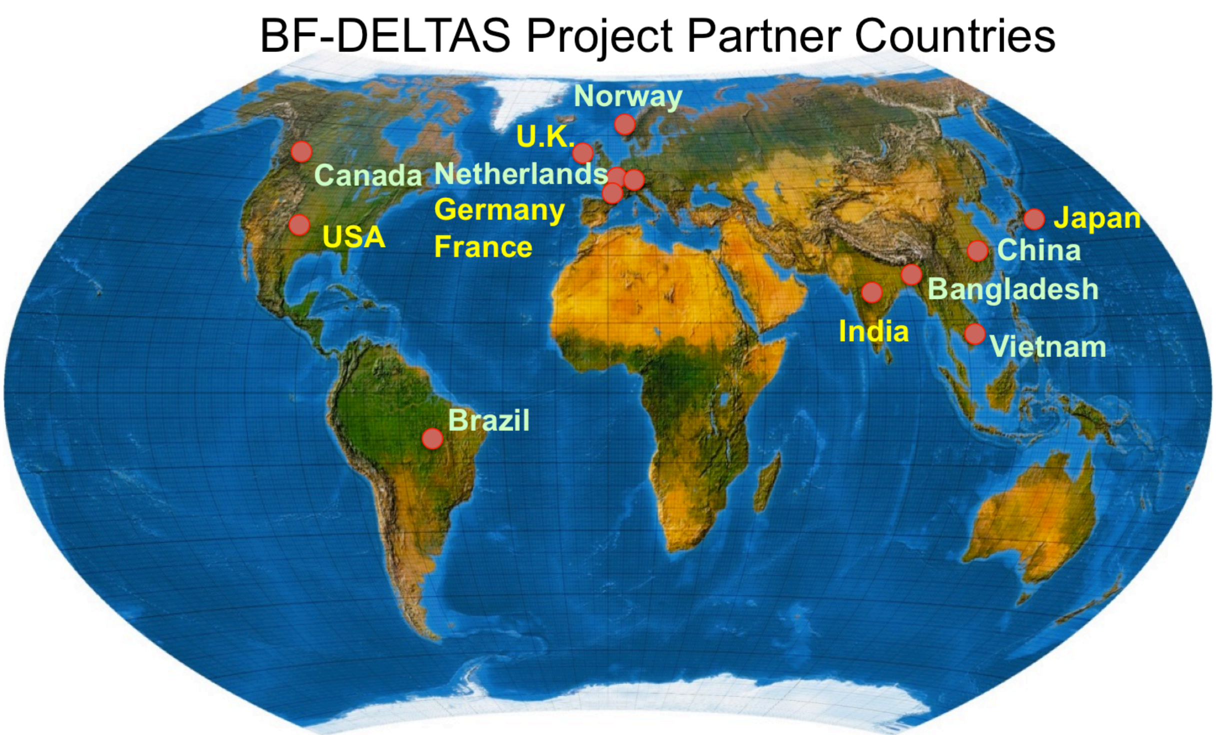
Vietnam: V. L. Ngugen (Vietnam Academy of Science and Technology); M. Goichot (World Wide Fund for Nature – Greater Mekong)

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

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)



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															

THEME	MAIN ACTIVITY TYPE	2013 Jan Mar	2013 Apr Jun	2013 Jul Sep	2013 Oct Dec	2014 Jan Mar	2014 Apr Jun	2014 Jul Sep*	2014 Oct Dec	2015 Jan Mar	2015 Apr Jun	2015 Jul Sep	2015 Oct Dec	2016 Jan Mar	2016 Apr Jun	2016 Jul Sep**
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 Coastal Zones (Foufoula–Georgiou)
2. Transport and Vulnerability in River deltas: a graph theoretic approach (Foufoula–Georgiou)
3. Web-based Delta Modeling (Overeem)
4. Subsidence and Sedimentation in Deltaic regions (Overeem)
5. Data needs assessment, Delta-DAT prototype database spreadsheet (Brondizio)
6. Data Acquisition and Processing: Spatial-temporal database construction for Amazon delta/estuary (Brondizio)
7. Definition of Amazon Delta/Estuary study site (Brondizio)
8. Delta Data Visualization, map products, figures and presentations (Brondizio)
9. Implementation and utilization of the iRODS server for the DELTAS project (Brondizio)
10. Compilation of Delta datasets for trend analysis and modeling (Kuenzer)
11. Analyzing coastal morphological changes in the Amazon Estuary (Kuenzer)
12. Detection and filling of cloud/cloud-shadow pixel in Landsat satellite images as a preprocessing step for land cover change detection analysis (Kuenzer)
13. Deltas-GDVI Structured Literature Review (Vorosmarty and Tessler)
14. Environmental Stress and Vulnerability analysis for deltas (Vorosmarty and Tessler)
15. Precipitation and surface inundation patterns in delta systems (Vorosmarty and Tessler)
16. Design and configuration of the Deltas-DAT data service (Vorosmarty and Tessler)
17. Selection and adaptation of a theoretical framework for delta resilience and vulnerability (Renaud and Sebesvari)
18. Identification and evaluation of a preliminary set of indicators for delta vulnerability assessment (Renaud and Sebesvari)
19. BF-DELTAS expert consultations on delta vulnerability indicator selection – Mekong Delta, 2-3 April 2014, Ho Chi Minh City, Vietnam (Renaud and Sebesvari)
20. Ganges-Brahmaputra River (GB) Delta Tidal Channel Processes (Goodbred Jr.)
21. Tide Wave Evolution and Tidal Harmonics on the GB Delta Plain (Goodbred Jr.)
22. Natural and Human-Induced Changes in GB Tidal Channel Network (Goodbred Jr.)
23. Flood Risk in Natural and Embanked Landscapes of GB delta plain (Goodbred Jr.)
24. Collation and correction of SRTM topographic data and adjustment to local cartographic and topographic datasets in deltas (Ramesh)
25. Collection of census data for economic, social, and demographic variables and association to geospatial data platforms for deltas (Ramesh)
26. Assimilation of data on flooding and sediment aggradation; habitat modification; climate change effects; demographics and socio-economics (Ramesh)

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

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

29. Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

30. Communication and outreach of delta socio-ecological research (Matthews and Szabo)

31. Preliminary data analysis of delta systems: demographic and budget surveys (Matthews and Szabo)

These PI contributions reported herein integrate under the 5 WPs as follows:

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

- A new Algorithm for Improved Satellite Rainfall Retrieval over Coastal Zones (Foufoula–Georgiou)
- Transport and Vulnerability in River deltas: a graph theoretic approach (Foufoula–Georgiou)

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

- Web-based Delta Modeling (Overeem)
- Subsidence and Sedimentation in Deltaic regions (Overeem)
- Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)
- Communication and outreach of delta socio-ecological research (Matthews and Szabo)
- Preliminary data analysis: demographic and analysis of budget surveys (Matthews and Szabo)

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

- Data needs assessment, Delta-DAT prototype database spreadsheet (Brondizio)
- Data Acquisition and Processing: Spatial-temporal database construction for Amazon delta/estuary (Brondizio)
- Definition of Amazon Delta/Estuary study site (Brondizio)
- Delta Data Visualization, map products, figures and presentations (Brondizio)
- Implementation and utilization of the iRODS server for the DELTAS project (Brondizio)
- Compilation of Delta datasets for trend analysis and modeling (Kuenzer)
- Design and configuration of the Deltas-DAT data service (Vorosmarty and Tessler)

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

- Deltas-GDVI Structured Literature Review (Vorosmarty and Tessler)
- Environmental Stress and Vulnerability analysis for deltas (Vorosmarty and Tessler)
- Precipitation and surface inundation patterns in delta systems (Vorosmarty and Tessler)
- Selection and adaptation of a theoretical framework for delta resilience and vulnerability (Renaud and Sebesvari)

- Identification and evaluation of a preliminary set of indicators for delta vulnerability assessment (Renaud and Sebesvari)
- BF-DELTAS expert consultations on delta vulnerability indicator selection – Mekong Delta, 2-3 April 2014, Ho Chi Minh City, Vietnam (Renaud and Sebesvari)

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

Delta-ACT Ganges: Steven Goodbred Jr.

- Ganges-Brahmaputra River (GB) Delta Tidal Channel Processes (Goodbred Jr.)
- Tide Wave Evolution and Tidal Harmonics on the GB Delta Plain (Goodbred Jr.)
- Natural and Human-Induced Changes in GB Tidal Channel Network (Goodbred Jr.)
- Flood Risk in Natural and Embanked Landscapes of GB delta plain (Goodbred Jr.)
- Subsidence and Sedimentation in Deltaic regions (Overeem)
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- 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)

Delta-ACT Mekong: Claudia Kuenzer

- Detection and filling of cloud/cloud-shadow pixel in Landsat satellite images as a preprocessing step for land cover change detection analysis (Kuenzer)
- Compilation of Delta datasets for trend analysis and modeling (Kuenzer)
- Data acquisition and data collection of socio-economic and demographic indicators in Mekong, GBD and Amazon (Matthews and Szabo)

Delta-ACT Amazon: Eduardo Brondizio

- Analyzing coastal morphological changes in the Amazon Estuary (Kuenzer)
- Definition of Amazon Delta/Estuary study site (Brondizio)
- Detection and filling of cloud/cloud-shadow pixel in Landsat satellite images as a preprocessing step for land cover change detection analysis (Kuenzer)

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 first 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.

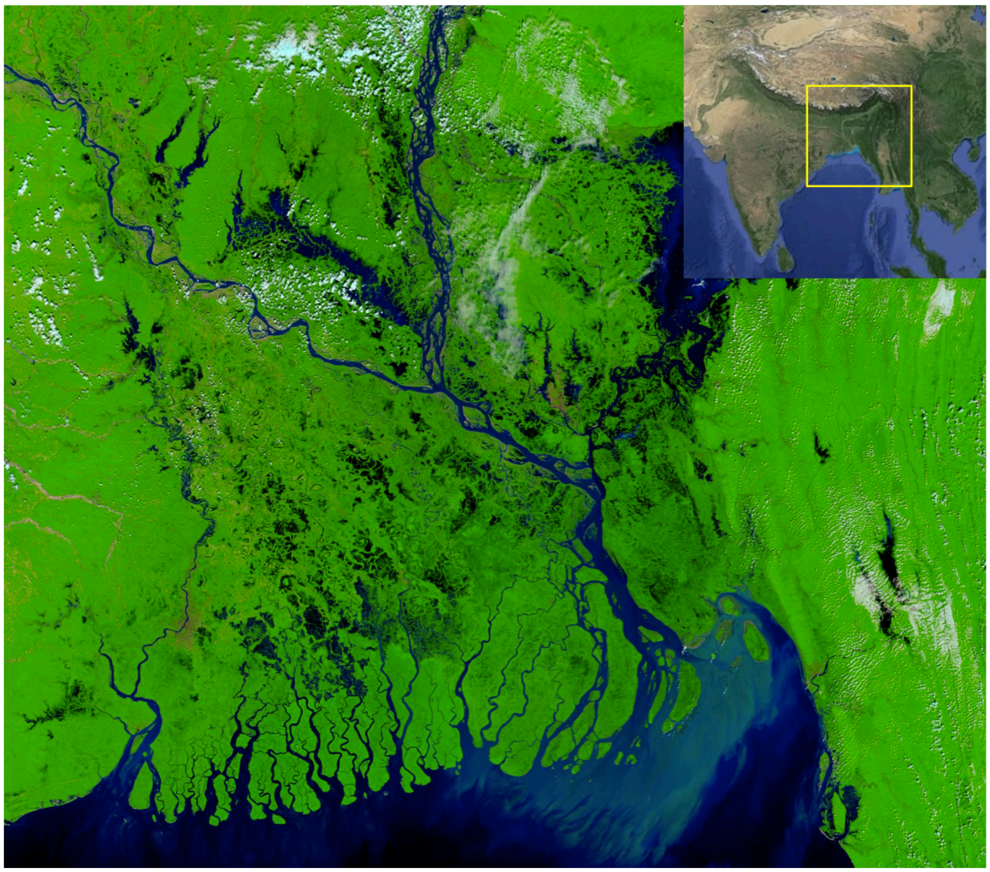
Integrated Work Package 5: Regional Implementation Case Studies (Delta-ACT)

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

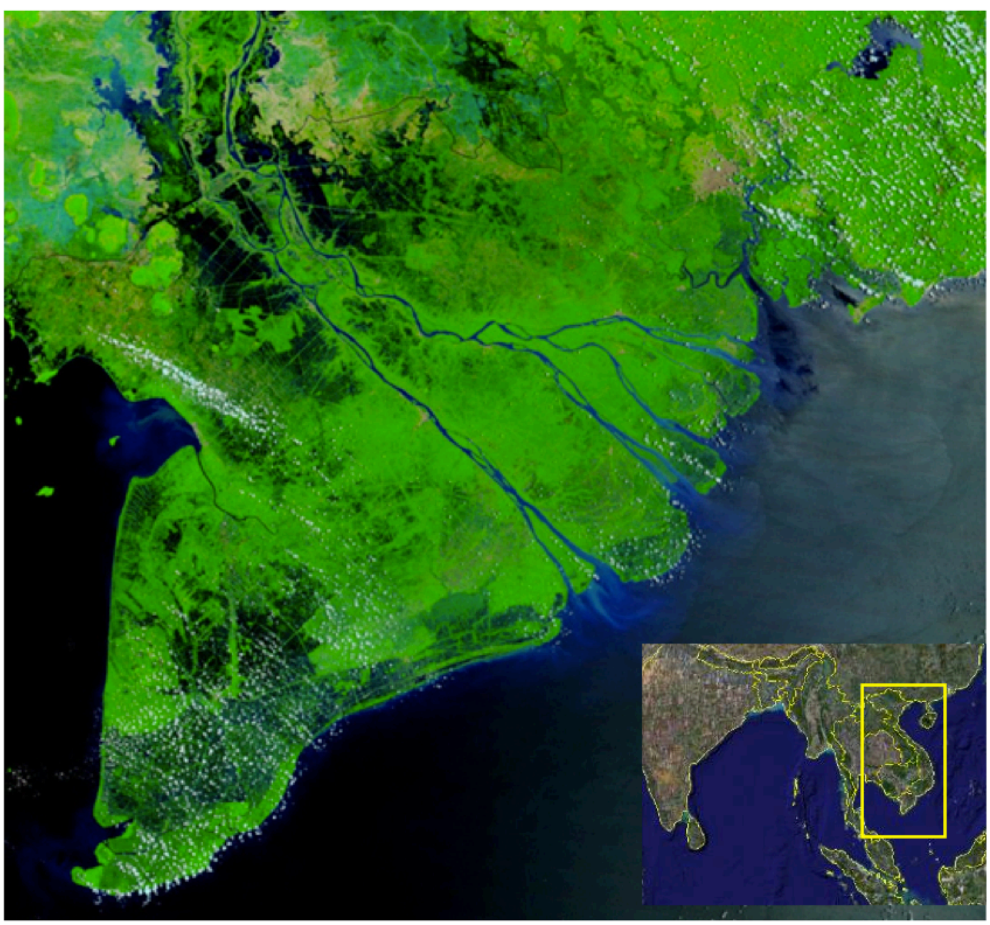
The GBM Delta is one of the world's largest (~100,000 km^2) and most dynamic deltas draining land from Bangladesh, Bhutan, China, India and Nepal. The delta covers most of Bangladesh and part of West Bengal, India, with many of the 147 million people (in 2000) living in the delta under extreme poverty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

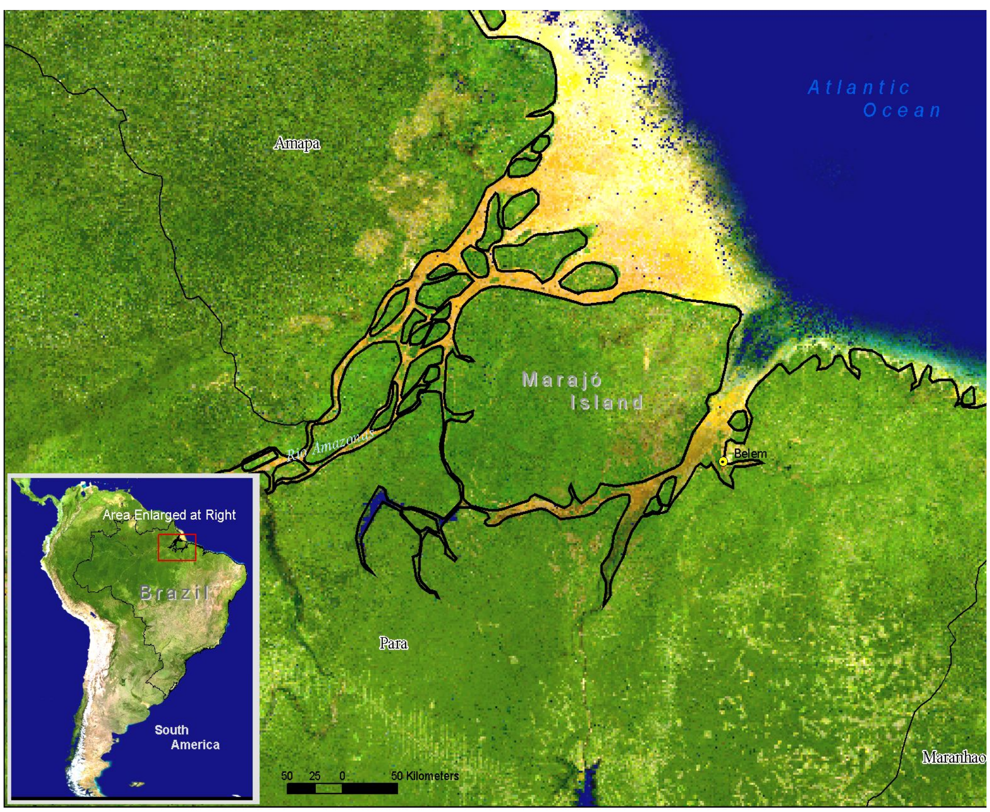
The Mekong Delta is considered as the world's third largest delta (with an area of 93,781 km^2 and population of 17 million), is one of Asia's main food baskets, and is second only to the Amazon in terms of fish biodiversity [*WWF*, 2008]. The major challenges in the MRD can be attributed to socio-economic 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, deforestation proceeds at a rapid pace, and population, economy, and infrastructure in Amazonia are growing quickly. Furthermore, the projected construction of dams, ports and aqueducts as part of the ongoing regional integration development policies is expected to impact water and sediment flow from large tributaries such as the Madeira and Xingu rivers to the ARD [*GeoAmazonia*, 2009]. The Amazonian basin is also currently under a massive plan for infrastructure transformation including continental cross-national highways, river and sea-ports, and a sequence of dams combining transportation river-ways and hydro-electrical plants. Ultimately, like all deltas, the ARD faces multiple, imminent environmental threats.



UNIVERSITY OF MINNESOTA
Driven to Discover℠

Efi Foufoula–Georgiou

University of Minnesota

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

Research Themes and Accomplishments during 2013-2014

Our research efforts over the past year 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 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 Coastal Zones

Accurate estimation of precipitation over deltaic regions is important for climate studies, flood prediction, sediment and nutrient transport, flood inundation mapping, and hazard control. Since observations from rain gauges and ground radars in these regions are lacking or are very sparse, satellites offer the only reliable source of information. Yet, while the accuracy of spaceborne microwave precipitation retrieval over oceans from microwave satellites, such as the TRMM (Tropical Rainfall Measuring Mission), has considerably improved over the past decades, accurate precipitation retrieval over coastal regions remains a challenge mainly due to the interference of land-ocean background radiations. Having accurate estimates of precipitation over coastal regions will improve our ability to understand the socio-ecological response of these vulnerable systems to extremes, make more accurate climate projections, and improve flood forecasting and risk management practices.

In view of the GPM (Global Precipitation Measuring Mission), a constellation of nine satellites whose core satellite was launched in Japan in February 2014, there is a great potential to improve the accuracy and space- time resolution of precipitation retrievals over land and complex topography, including land-water interfaces. This will require the development of new methodologies.

We have developed a new approach to the inverse problem of passive microwave rainfall retrieval. The proposed methodology relies on modern supervised manifold learning and regularization paradigms, which makes use of two joint dictionaries of coincidental rainfall profiles and their upwelling spectral radiative fluxes. A sequential detection-estimation strategy is adopted which relies on a geometrical intuition that similar rainfall intensity values and their spectral radiances lie on or live close to some sufficiently smooth manifolds with analogous geometrical structure. The detection step employs of a nearest neighborhood classification rule, while the estimation step relies on the modern developments in manifold learning and regularized estimation paradigms and uses a constrained shrinkage estimator to ensure sufficiently stable retrieval and some physical consistency. The algorithm makes use of two joint dictionaries, the spectral and rainfall dictionaries, containing elements or atoms of spectral responses of different rainfall profiles.

The algorithm has been tested using coincidental observations of the active precipitation radar (PR) and passive microwave imager (TMI) on board the Tropical Rainfall Measuring Mission (TRMM) satellite. We document improved instantaneous retrieval results for a wide range of storms over ocean, land, and coastal zones and demonstrate that the algorithm is capable of capturing high-intensity rain-cells and sharp gradients in storm morphology. The algorithm is also compared at an annual scale for calendar year 2013 versus the current standard rainfall product 2A12 (version 7) of the TRMM and marked improved retrieval skill is reported.

Future components of this research, planned for 2014-15 include:

i. Identification of all the TRMM overpasses over Ganges, Mekong, and Amazon for a five-year period (initially and longer periods later) and obtaining the TMI (passive sensor) and PR (active sensor) data from NASA's TRMM web site.
ii. Application of the 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).
iii. Collaboration with the team of Prof. Steven Goodbred Jr. at Vanderbilt University to obtain rain gauge data in the Ganges for validation of the retrieval algorithm.
iv. Collaboration with the team at CUNY to develop a methodology for computing inundation maps for deltas given the detailed space-time distribution of precipitation and satellite data for topography and land-use.

2. Transport and Vulnerability in River deltas: a graph theoretic approach

Water, sediment, and nutrient fluxes that nourish and sustain deltaic systems are delivered throughout its "body" via multiple pathways some of them natural and some of them human engineered. Demands on water and energy upstream are satisfied thanks to dams and divergence structures, while multiple dykes, embankments and sluice gates are constructed downstream mainly for irrigation purposes and to control floods and salinity intrusion. To maintain a desired socio-ecological state of a delta, material and energy fluxes must be delivered to its body and to its coastal zone in a way that "malnourishment" is avoided, as this would compromise system integrity, which often is not local but propagates to larger areas.

In contrast to the well-studied topology of tributary channel networks (networks that drain to a single outlet), the exploration of the topology of distributary channel networks (networks that originate from a single source and drain to multiple outlets) is still in its infancy. Yet, this topology defines the distribution of network fluxes and dictates how changes in a given part of a network propagate to the rest; it also paves the way to better understand the intricate self-organization of deltaic systems.

We have developed a framework for analyzing the topology of delta networks, and specifically for identifying the upstream and downstream subnetworks for any given vertex, computing steady-state flux propagation in the network, and performing vulnerability analysis by assessing parts of the network where a change would most significantly affect the downstream or shoreline fluxes. Dam construction can be emulated by reducing water and sediment downstream by a given fraction, the location and operation of irrigation dykes can be varied, and different alternative management options can be evaluated in a simple yet spatially extensive framework. A vulnerability map is constructed wherein sediment and water delivery to the coastal zone outlets is mapped against hundreds of upstream nodes. This enables us to evaluate which nodes and what management scenarios would most influence (positively or negatively) flux delivery to the coastal nodes. Localized or more spatial extensive interventions can be explored and a whole systems approach to management can be developed.

Our methodology uses a graph-theoretic framework, by which a deltaic system is mapped into a complex set of inter-connected pathways (network) of material and energy fluxes. Notably, all the results follow directly from the spectral decomposition of the Laplacian (or weighted Laplacian) for the graph representing the examined delta. Although we focus on the steady-state topology of a delta that does not directly incorporate the dynamic evolution of the channel morphology or its topology, extension of the framework to incorporate time-evolving adjacency matrix is possible. The proposed framework can form a basis for delta network topology classification and for defining comparative vulnerability metrics among different deltas as well as for the same delta under natural and/or human-induced changes.

We illustrate this framework with the Wax Lake and Niger deltas. The Wax Lake delta is a relatively young river-dominated delta with a radial shoreline propagation (Fig. 1). It directly receives input from the Wax Lake outlet with an average discharge of 2,783 m3/s and between 25 and 38 MT/yr of sediment. The delta is a product of the diversion of the Mississippi River in the 1970s and since then it has evolved with minimum human alteration. We utilize the outline of the Wax Lake delta structure processed by *Edmonds et al.* [2011]; it has 59 links and 24 shoreline outlets. The partition of the flow at a node among the immediate downstream channels is proportional to the channel width [*Bolla Pittaluga et al.,* 2003; Edmonds *et al.,* 2011]. The Niger delta is an older, highly complex distributary network that contains numerous loops and other intricate structures. We consider the area outlined by *Smart and Moruzzi* [1972]; it has 180 links and 15 shoreline outlets. In absence of the channel width data, we use equal partition of the flow among the immediate downstream channels.

The steady state flux for the Wax Lake delta is illustrated in Fig. 2(a). There exists no dominant shoreline outlet for this delta – the maximum outlet flow of about 12% of the apex flux is achieved at 4 out of 24 outlets. The flux at the shoreline shows that 25% (6 out of 24) of outlet links receive 60% of the flux at the apex. This result is comparable to the synthetic sediment flux distribution at the shoreline for the Wax Lake delta obtained by *Edmonds et al.* [2011]. The steady state flux for the Niger delta is illustrated in Fig. 2(c). This delta has a singe dominant outlet that receives 50% of the apex flux, with the second largest outlet receiving 12%. Figures 2(b), (d) show the number of outlets a given link contributes to in the two examined deltas. This plot highlights the relative importance of a link in the delta network: the *hotspot* (red) links affect many outlets while blue links only affect a single outlet. The *hotspots* can be interpreted as "highways of perturbation" since, even if the steady flux in the link is not high, the effect of the perturbation will be experienced by many shoreline outlets in the delta. Representative examples of the outlet contributing networks are highlighted in Fig. 3(a)-(d) (where the colors should be ignored for now). In the Wax Lake delta, most of the outlet contributing networks (18 out of 24, or 67%) have a single path connecting the delta apex to the shoreline outlet. On the contrary, in the Niger delta all the networks have multiple pathways.

Flux reduction is recurrent in deltas due to dams and impoundments. Once a flux is reduced at a specific part of the delta, the change of flux in the entire delta is computed using our methodology. We are interested in identifying "vulnerable" links defined as the links whose flux reduction would cause the highest reduction at the outlets. For that we compute the flux reduction at the outlets caused by an $\alpha = 0.4$ flux reduction at a given link, considered one-by-one. The results are illustrated in *vulnerability maps* for the representative subnetworks in Fig. 3. The links colored red, yellow, and blue represent high (r > 40%), medium (20% < *r* < 40%) and low (r < 20%) flux reduction at the shoreline outlet, respectively. In general, if a given link drains $p \cdot 100\%$, $0 \leq p \leq 1$, of its flux to a given outlet, and the steady flux *fold* at the link is related to the steady flux *gold* at the outlet as *fold* = *Cgold, C* > 0, then *α-reduction* at this link results in the outlet reduction *fnew* = *fold* (1 - *α p C).* Here, *α* is a local characteristic of the link, while both *C* and *p* are spatially extended pairwise characteristics of the link and the examined outlet. We also notice that in multi-paths networks (Fig. 3 except (c)) the vulnerability might not be monotone along individual downstream channels. These observations support the necessity of a systematic, spatially extended approach to studying the effects of link modifications.

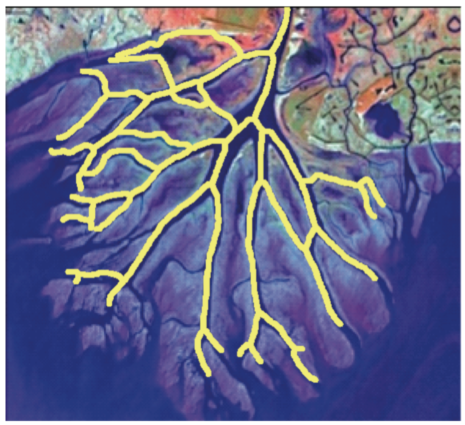


Figure 1. Wax Lake delta. The skeleton network (yellow lines) is superimposed on the aerial view of the delta in 2005 by the National Center of Earth-surface Dynamics (NCED). Only links in the network that connect the delta apex to the shoreline outlets are considered in the connectivity analysis.

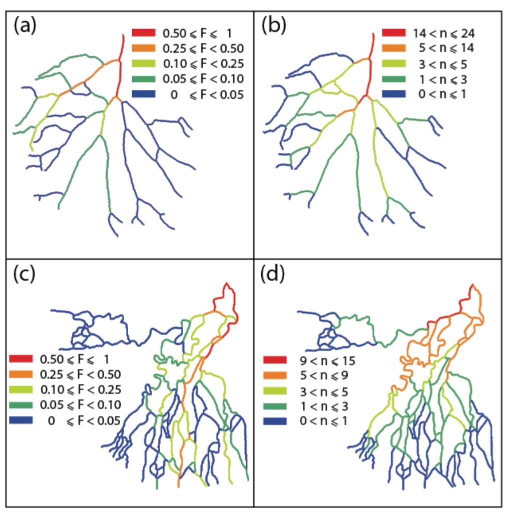


Figure 2. Steady state flux (a, c) and number of outlets (b, d) that a given link contributes to. (a, b) Wax Lake delta: The distribution of flux among the immediate downstream links is proportional to the channel width. (c, d) Niger delta: flux is distributed equally among the immediate downstream links. Flux at the apex is normalized to *F* =1.

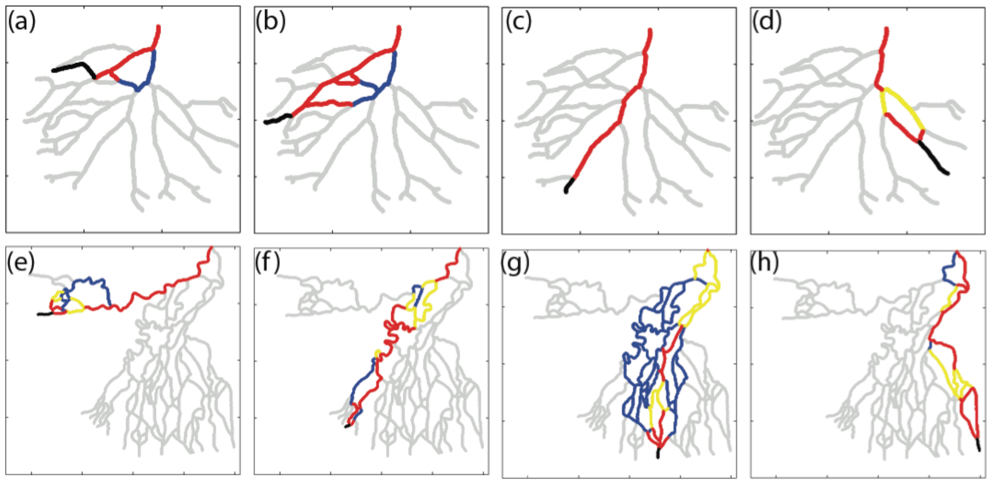


Figure 3. Vulnerability maps for the Wax Lake (a-d) and Niger (e-h) deltas. Each panel highlights the contributing network for a single outlet. Shoreline outlets are shown in black. Red, yellow, and blue links represent high (r >40%), medium (20%< r <40%) and low (r < 20%) reduction to the shoreline outlet, respectively, where a 40% flux reduction is applied to the link.

Future components of this research, planned for 2014-15 include:

i. Acquiring SRTM topography data and extracting the channel network for parts of the Ganges, Mekong, and Amazon river deltas. The whole network in the GBM is too large to be able to extract it automatically but UMN plans to collaborate with Prof. Paola Passalacqua at the University of Texas, Austin who has developed a methodology for channel extraction and has tested it in the GBM.

ii. Further developing the theoretical foundations of the graph-theoretic framework for analyzing complex deltaic channel networks and testing it for robustness in computing the sub-networks and vulnerability maps.

iii. Pursuing a network approach to developing integrated metrics for delta comparison and for assessing whether a particular network topological structure is more (or less) vulnerable than another. The first case study will be the Wax lake delta for which air photos 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.

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University of Colorado Boulder

Irina Overeem

Community Surface Dynamics Modeling System

With contribution from Stephanie Higgins, Kimberly Rogers

Research Themes and Accomplishments during 2013-2014

Research in 2013-2014 has focused both on development of an integrated modeling framework, and on delta specific process modeling. We have integrated studies of remote-sensing data, 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). Ultimately, the developed models are integrated into an open-source, freely available web-based modeling framework being developed within the context of the Community Surface Dynamics Modeling System. Application of the developed modeling framework 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. Web-based Delta Modeling

The CSDMS open-source modeling framework (developed under separate NSF-funding) forms the foundation for an applied framework for delta modeling. CSDMS released a new open source Web-based Modeling Tool, called WMT, in May 2014. WMT is a user-friendly way of interacting with the CSDMS model coupling framework.

The *CSDMS model coupling framework* allows developers to write applications that connect components to one another to form new models [*Syvitski et al.*, 2014]. CSDMS helps develop stand-alone codes into connectable interoperable *components* that allow models written in different languages (C, C++, Fortran, Python, and Java) to communicate. A stand-alone model (for example a model of a specific delta process such as subsidence) needs a 'Basic Model Interface' (BMI). The BMI addresses the interaction of components that operate within a shared memory space by providing entry points for: 1) component control (initialize, run, and finalize steps), 2) data access, and 3) metadata. A component that implements a BMI provides entry points into an underlying model to allow existing models to couple with other community models that expose a BMI. Once a numerical model is wrapped with a Basic Model Interface, components are then wrapped with a 'Component Model Interface' (CMI) and have full access to software framework services and can be connected to 'service components' for general tasks, like regridding and file I/O. Within the context of this Belmont Forum project we strive to add components with relevance for delta modeling.

With the newly released WMT, new users can simply use their internet browser to set up and submit simulations with models that are compliant to the CSDMS framework. 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.

WMT makes it easy to:

- Select a component model from a list to run in standalone mode,
- Build a coupled model from multiple components,
- View defaults and edit the parameters for these model components,
- Upload custom input files to the server,
- Share saved models with others in the community, and
- Run a model by connecting to a remote HPCC where the components are installed.

WMT is tightly integrated with model metadata, model help pages, and tutorials to ensure that models do not become a black box. It is of crucial importance to know the level of process simplification within a model engine and the implementation into equations and a numerical scheme. Without such transparency the analysis of model output is of much less value. Consequently, WMT components are documented in detail on the CSDMS wiki. With WMT, a user can access: 1) more extensive model description, 2) notes on input parameters, 3) key model equations, 4) notes on coupling ports, and 5) essential references provided by the original developer.

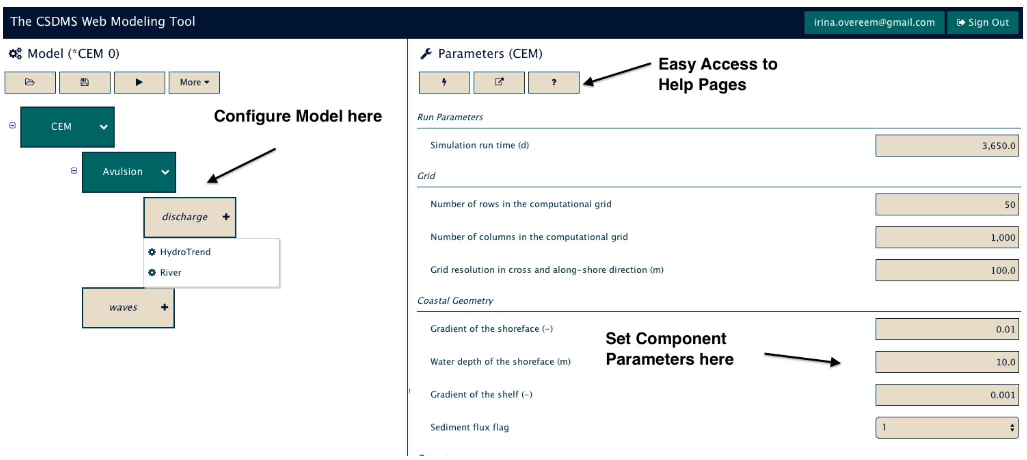

Figure 1. Example of Web-based Modeling Tool User Interface showing a coupled model simulation between a river discharge model, a distributary channel model and a 2-dimensional coastline evolution model (CEM).

The WMT will be the foundation for delta modeling in the context of this project. Exercises of relevant delta environmental models have been developed online: HydroTrend, Plume, Sedflux, CEM.

In the next year the UCB team will focus on the following components of the WMT:

- Adding example projects for Mekong, Amazon and Ganges delta with existing HydroTrend component as demonstration projects on climate change and reservoir/land-use changes.
- Bringing sedimentation model into the CSDMS web-based modeling tool and couple it to HydroTrend model and possibly a longterm delta model.
- Develop service components to access GIS delta data for model simulations.

2. Subsidence and Sedimentation in Deltaic regions

Many of the world's river deltas are sinking due to groundwater extraction, hydrocarbon extraction, reduced sediment supply, and natural sediment loading and compaction processes. Little is known, however, about the full spatial variability of subsidence rates in complex delta systems. The UCB team reconstructed subsidence rates in the Yellow River delta and demonstrated the profound influence of fish farming on coastal stability [*Higgins et al.*, 2013].

The University of Colorado at Boulder (UCB) team has lead analyses on subsidence and sedimentation in the GBM. The UCB team has mapped subsidence in the eastern portion of the GBD, Bangladesh, covering more than 10,000 km^2 at a high spatial resolution of 100 m. Subsidence maps have been produced using remotely-sensed Interferometric Synthetic Aperture Radar (InSAR) covering the period 2007 to 2011. Eighteen ALOS (Advanced Land Observing Satellite) PALSAR (Phased-Array L-band SAR) scenes were used to generate 30 interferograms calibrated with in-situ GPS. Interferograms were stacked to yield average subsidence rates over the study period and validated against an additional GPS record from Dhaka, Bangladesh. Land subsidence of 0 to > 10 mm/y is seen in Dhaka, with variability likely related to local variations in shallow subsurface sediment properties. Outside of the metro-area, rates vary from 0 to > 18 mm/y, with the lowest rates appearing primarily in Pleistocene Clay and the highest rates in younger Holocene organic-rich muds. These results demonstrate that subsidence patterns in this delta are primarily controlled by local stratigraphy, with rates varying by more than an order of magnitude depending on lithology. The ability of L-band InSAR to differentiate between stratigraphic units in this humid, vegetated subtropical river delta demonstrates the power of interferometry as a tool for studying the subsurface in deltaic environments [*Higgins et al.*, 2014].

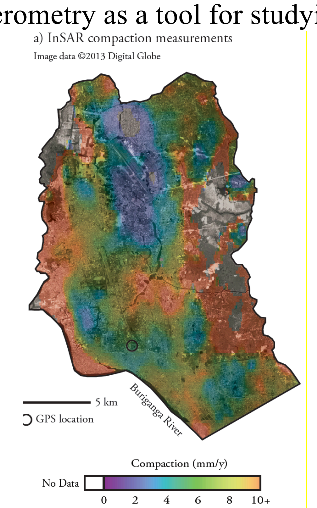

Figure 2. InSAR mapping of subsidence (Higgins et al, 2014). Subsidence rates in the Ganges-Brahmaputra delta, Dhaka region show rates of subsidence varying between 1-10 mm/year

Similar to subsidence patterns, downstream spatial distribution of sediments into the deltaic distributary channel network and deposition rates onto the floodplain and delta plain are remarkably unconstrained, yet of critical importance to the understanding of the overall delta sediment budget. Again as an example, the monsoon-driven Ganges-Brahmaputra river system transports large amounts of sediment from the Himalayas to the delta. We numerically modeled incoming sediment flux with a 1D climate-driven hydrological model HydroTrend. The model uses basin-averaged conditions of climatology to calculate the water balance and routes water and sediment throughout the Ganges and Brahmaputra drainage basins. The estimated flux provides a boundary condition to the lowland delta system (and downstream coupled models). We presented a simple approach to sediment routing over the delta distributaries and into tidal channels; we use channel network characteristics to distinguish between three orders of channels and route suspended load according to their planview dimensions. In the tidal delta, we reverse our simple routing scheme with sediment flux coming from the nearshore water. Characteristics of associated islands, such as nearest-edge to water distance, are determined for each of the characteristic channel order classes. We then use two cross-sectional process models, AquaTellUS and FV-SED, to calculate cross-channel sediment flux deposited on delta islands during river flooding and tidal flooding.

We showed that monsoonal flooding and a high tidal range are highly efficient mechanisms to re-deposit sediment onto the delta plain, especially in areas of high channel connectivity in the coastal zone. This finding is corroborated by collected field data on sedimentation rates in the coastal zone, which highlighted that over a single monsoonal season as much as 1 cm/yr of sediment is deposited widespread in the tidally-controlled areas of the abandoned Western delta. Preliminary field data in the fluvial-dominated reach shows higher sedimentation rates locally (~5 cm/yr), but exhibits a more spatially varied sedimentation pattern. These results are comparable to rapid near-channel sedimentation as indicated by the numerical modeling (Figure 3). Our simplified concept helps highlight unknowns in the active deltaplain sedimentation rates of the Ganges-Brahmaputra delta.

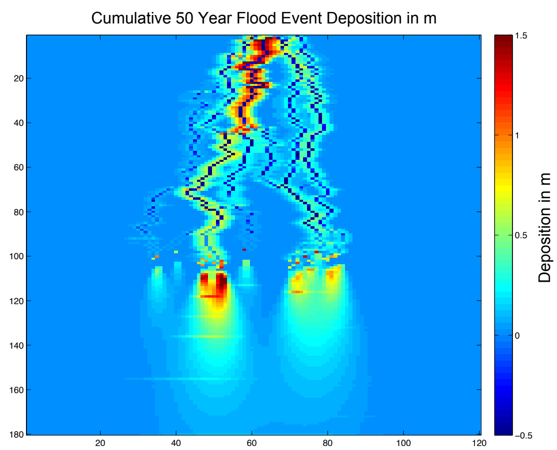

Figure 3. AquaTellUs model predictions of floodplain deposition for different order of distributary delta channels [*Overeem et al.*, 2014].

In the next year the UCB team will further develop their analyses of sedimentation and subsidence in deltas, so that these data can be integrated into the modelling tools, specifically as follows:

- Enhance the sedimentation model and combine with routine for high-frequency low magnitude floods, versus low-frequency high magnitude floods.
- Design a subsidence model for use in delta environments.

Publications 2013-2014 (partially funded by this grant)

Brakenridge, G.R., Syvitski, J.P.M., Overeem, I., Higgins, S. A., Kettner, A.J., Stewart-Moore, J.A., Westerhoff, R., 2013. Global Mapping of Storm Surges and the Assessment of Delta Vulnerability, *Natural Hazards*. 66:1295-1312.

Foufoula-Georgiou, E., I. Overeem, Y. Saito, S. Dech, C. Kuenzer, S. Goodbred, I. Harrison, E. Anthony, E. Brondizio, J. Hutton, R. Nicholls, Z. Matthews, J. Dearing, A. Lazar, A. Baschieri, A. Newton, R. Ramachandran, F. Renaud, Z. Sebesvari, C. Vorosmarty, Z. Tessler, S. Costa, K. M. Ahmed, M. M. Rahman, G. Lintern, P. Van Cappellen, H. Durr, S. Gao, M. Marchand, T. Bucx, V. L. Nguyen, M. Goichot, C. Paola, D. Mohrig, and R. Twilley (2013), A vision for a coordinated international effort on delta sustainability, in Deltas: Landforms, Ecosystems and Human Activities, edited by G. Young & G.M.E. Perillo, IAHS Publ. 358, 3-11.

Higgins, S., Overeem, I., Steckler, M., Syvitski, J., (online 2014). InSAR Measurements of Compaction and Subsidence in the Ganges-Brahmaputra Delta, Bangladesh. *Journal of Geophysical Research.*

Higgins, S. A., Overeem I., Tanaka, A., Syvitski, J.P.M., (2013). Land Subsidence at Aquaculture Facilities in the Yellow River Delta, China. *Geophysical Research Letters*. 40,15, 3898-3902.

Hossain, A. 2013. Assessing Morphological Changes due to Hydrometeorologic Influences in Mehendiganj Island, Meghna Estuary, Bangladesh. *M.Sc. Thesis* for Faculty of Earth and Environmental Sciences, University of Dhaka, Bangladesh joint with University of Colorado, Boulder.

Rogers, K., Syvitski, J., Overeem, I., Higgins, S., 2013. Farming Practices and Anthropogenic Delta Dynamics. in Deltas: Landforms, Ecosystems and Human Activities, edited by G. Young & G.M.E. Perillo, IAHS Publ. 358.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Giosan, L., Brakenridge, R., Hannon, M. *, Bilham, R., (2014). The Anthropocene Metamorphis of the Indus Delta and Lower Floodplain. *The Anthropocene.*

Syvitski, J.P.M., Hutton, E., Piper, M., Overeem, I., Kettner, A.J., 2014. Plug and Play Component Modeling — The CSDMS2.0 Approach. International Environmental Modelling and Software Society (iEMSs), Extended abstract for 7th International Congress on Environmental Modelling and Software, San Diego, California, USA.

The code of the CSDMS Web Modeling Tool is open-access and available for other developers through a version-control system:

https://github.com/csdms/wmt

Conference presentations and abstracts:

Foufoula-Georgiou, Efi, A. Tejedor, A. Longjas, I. Overeem, F. Renaud, and J. Dearing, 2014, Constructing vulnerability maps of material and energy pathways in deltas, in: Deltas in times of climate change II international conference, Rotterdam, Netherlands, 24-26 September.

Higgins, S., Overeem, I., Syvitski, J., 2013. Land Subsidence at Aquaculture Facilities in the Yellow River Delta, China. CSDMS Annual Meeting, Boulder, CO, March 23-25th, 2013.

Kettner, A., Syvitski, J., Overeem, I., Brakenridge, R., 2013. Flood deposition patterns and channel migration due to a 10-year flood event: the case of the Indus River Flood 2010. AGU Annual Meeting, San Francisco, Dec 9-13, 2013.

Overeem, I., Rogers, K., Passalacqua, P., Canestrelli, A., Cohen, S., Matin, K., 2014. Sedimentation Patterns in the Ganges-Brahmaputra Delta System. AAPG International Meeting, Houston, TX, April 6-9th, 2014.

Overeem, I., K. Rogers, C. Thorne, Sarker, M., M. Steckler, S.Goodbred, C. Wilson, C. Small, M.van der Wegen, D. Roelvink, J.Atkinson, M. Zahid, N. Seeber, S. Nooner, J. Davis. 2014. Monitoring, Research and Analysis of the Bangladesh Coastal Zone, Worldbank Coastal Embankment Improvement Project Division, Dhaka, Bangladesh, March 2, 2014.

Overeem, I., Kim, W., 2013. Understanding coupled earth-surface processes through experiments and models. AGU Annual Meeting, San Francisco, Dec 9-13, 2013.

Overeem, I., Rogers, K., Goodbred, S., Passalacqua, P. 2014. Sedimentation in the Ganges-Brahmaputra Delta: natural mangrove forest and embanked polders. Deltas in times of Climate Change II, International Conference, Rotterdam, The Netherlands, 24-26th of September, 2014.

Rogers, K., Overeem, I., 2013. Modeling Floodplain Dynamics: Can the Ganges-Brahmaputra Delta keep up with 21st century sea level rise? AGU Annual Meeting, San Francisco, Dec 9-13, 2013.

Rogers, K., Overeem, I., 2014. Modeling floodplain dynamics: Can the Ganges-Brahmaputra Delta keep pace with 21st century sea level rise? CSDMS Annual Meeting, Boulder, CO, March 23-25th, 2013.

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

Research Themes and Accomplishments during 2013-2014

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

Since the beginning of the project two main datasets have been acquired. These include the Bangladeshi Household Income and Expenditure Survey (HIES) and Vietnamese Household Living Standards Survey (HLSS). In addition, hard copies of the 1989 edition of the Vietnamese census have been purchased.

Data collection started focusing on the Bangladeshi Ganges Brahmaputra Delta (GBD). Socio-economic and demographic indicators are being collated 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).

Initial inquires have been made to the Brazilian Statistical Office (IBGE).

2. Communication and outreach of delta socio-ecological research

Since the start of the project 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.

Potential collaboration with the Mekong Development Research Institute (MDRI) is being envisaged. To that aim a collaboration agreement has been drafted and shared with the MDRI for input.

3. Preliminary data analysis of delta systems: demographic and budget surveys

The main focus areas of the analysis undertaken include: demographic analysis and socio-economic analysis.

<u>Demographic analysis</u>

Demographic projections are now nearly finished starting for selected districts of the coastal GBD. As soon as BF delta boundaries are defined, this analysis can be expended for other districts within Bangladesh, and at a later stage for other delta regions.

<u>Analysis of budget surveys</u>

Another key aspect of BF-related work at the University of Southampton involves analysis of household survey data. To date, due to the lack of definition of delta regions, the analysis focused on the costal GBD. Two papers are being prepared investigating food security determinants in the region. Further analysis will focus on migration, health and food security issues within and across the three deltas.

Abstracts submissions and session proposals

To date the following conference abstracts have been submitted:

- Rural development and food insecurity in the Ganges Brahmaputra Delta: Challenges and prospects submitted to Deltas in Times of Climate Change: Connecting world science and deltas (September 2014, Rotterdam) [**accepted**]

- *Food Insecurity in the Rural Ganges Brahmaputra Delta: Challenges and Prospects* submitted to IDRC Davos 2014 (August 2014) [**accepted]**

- *Do households in environmentally vulnerable deltas experience greater inequalities in food security status? The case of the coastal Ganges Brahmaputra delta in Bangladesh* submitted to Inequality – measurement, trends, impacts, and policies (UNU Wider Development Conference, September 2014, Helsinki) [in process]

In addition, the following session proposal has been submitted:

- *Livelihoods and Ecosystem Services in Vulnerable Delta Regions: Implications for Policy and Practice,* submitted to 2014 AGU Fall Meeting in collaboration with Sandra da Costa from Universidade do Vale do Paraíba (UNIVAP) [in process]

Plans for the next six months
Priorities for the next six months include the following:

<u>Finalising the definition of DELTA boundaries:</u>
Professor Dearing has been contributing to the debate and is currently working with colleagues on finalising the geographical and social definitions of delta boundaries.

<u>Fast track papers:</u>
- Data collection and analysis for the FT paper 1;
- Data collection and analysis for the FT paper 2.

<u>Conference abstracts and proposals in preparation:</u>
Abstracts and a session proposal are being developed for the following conferences:
- Annual Conference of the Population Association of America (San Diego, April 2015);
- Asian Population Conference (Kuala Lumpur, July 2015).

A meeting with Bangladeshi partners and DFID representatives in Dhaka is planned for June 2014.

Eduardo S. Brondizio and Scott Hetrick

Indiana University

Research Themes and Accomplishments during 2013-2014

1. Data needs assessment, Delta-DAT prototype database spreadsheet

The Indiana University (IU) team created a prototype spreadsheet to assist with data needs assessment and acquisition of bio- physical and socio-economic datasets to be utilized by the research teams at large. This spreadsheet was shared with the group for review and comments/input.

2. Data Acquisition and Processing: Spatial-temporal database construction for Amazon delta/estuary

The IU team have collected and integrated comprehensive multi-temporal biophysical and social data in a Geographic Information Systems (GIS). They have acquired and processed multiple raster, vector and tabular datasets for use in analysis of the Amazon Delta. These data were collected and integrated at two levels of analysis: municipality and census sectors (the most disaggregated census unit in Brazil).

Assembled data included:

- Administrative limits for municipalities and census sectors for the Amazon delta and their changes since 1960
- Land cover 2000-2010
- Social, demographic, economic: Census Municipal and Census sectors 1990- 2000-2010. We are currently working with collaborating institution UNIVAP on completing data collection for all urban areas of the Amazon delta.
- Infrastructure: municipal infrastructure such as water, electricity, sanitation
- Production [agriculture, fisheries, forestry]: completed at the municipal level for the years 1990-2000-2010. We are currently working on assemble the same set of data for 1980, 1970, 1960.
- Rivers and watersheds: using the definition of the Brazilian Water Agency (ANA), we assembled spatial layers for all rivers and watersheds (categories I to IV) for the entire Amazon delta
- In addition to the above, several datasets were acquired related to delta morphology, climate, ecosystems and biodiversity, protected areas and indigenous lands, among other thematic sets.

In particular, three decades of tabular demographic census data were collected at various scales administrative aggregation, along with associated spatially explicit vector based GIS datasets and processed for use in GIS through joining tabular and vector datasets for spatial analysis.

Multi-temporal land cover data was acquired and processed. In particular multiple tiles of forest change data from 2000 through 2012 developed by U of Maryland and Google. Tiles were mosaicked and forest change data was tabulated based on administrative boundaries.

Multiple tiles of topographic data [SRTM data] were acquired through CGIAR, mosaicked and processed for analysis. This data was also used to generate topographic models for the Amazon delta and 3D visualization of the delta area.

3. Definition of Amazon Delta/Estuary study site

Through the use of delta definitions documented by Ericson, J. P., Vörösmarty, C. J., Dingman, S. L., Ward, L. G., & Meybeck, M. (2006). Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change, 50(1–2),* 63–82, and refined by Zachary Tessler at CCNY, the IU team was able to create spatially explicit delta definitions based on bio-physical and associated socio-economic administrative boundaries. To refine this definition, we also used hydrological data acquired from Brazil's national water agency and administrative units acquired from Brazil's Institute of Geography and Statistics.

4. Data Visualization, map products, figures and presentations

Several map products and figures have been produced to help project team members visualize the Amazon Delta definitions, features within the study area, hydrology and delta basins, and topography. These figures have been included in presentations and shared with the research teams at large. These figures are serving as the basis for two fast track papers described below.

5. Implementation and utilization of the iRODS server for the DELTAS project

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. Relevant datasets collected for the Amazon study area have been and continue to be uploaded.

Future work

We accomplished the main goals planned for the first year of the project, 2013-2014. By assembling DELTAS-DAT for the Amazon delta area we developed a solid foundation to support data analysis, student research, and other components of the Deltas project, such as on modeling and scenario building. In preparation for the second year of the project, we are focusing on:

1. Data analysis of historical trends in social-demographic, economic, and land use and land cover change. This material will be used for the project's fast-track paper 1 on comparative trends across the three delta study sites.

2. Data analysis of the spatial matching of socio-ecological, hydrography, and institutional units of analysis of the Amazon delta. This material will be used for the project's fast-track paper 2 on the "fit" of socio-ecological and institutional units of analysis of the Amazon delta.

3. At the start of year 2 of the project, we will invest time on developing an online GIS for the project, that can be interactive and available to all research teams involved with the project as well as stakeholders and other users.

4. Brondizio will visit the Amazon delta from June 25 to July 1 to discuss collaborations with local researchers and to carry out short field visits in areas where intensive data collection is underway (supported by another project).

5. We will continue and expand activities of capacity building and student mentoring, including integrating one doctoral student and one undergraduate student at Indiana University into the project.

Project related presentations and publications

The following publications are associated, directly or indirectly, to the project:

Brondizio, E. S. 2014. Abordagens teóricas e metodológicas para o estudo de mudança de Usos da Terra. In *Ambiente e Sociedade na Amazonia : Uma Abordagem Interdisciplinar.* E. Vieira, P. Toledo, e R. Araujo. Belem, Brazil : Editora do Museu Paraense Emilio Goeldi.

Connections : this article was written as a request of research collaborators in the Amazon delta region to be part of a book in Portuguese on interdisciplinarity in human-environment studies. Several examples used in the book relate to the data organized for DELTAS-DAT.

Brondizio, E. S. 2013. A microcosm of the Anthropocene: Socioecological complexity and social theory in the Amazon. *Perspectives:* Journal de la Reseaux Francaise d'Institut d'études avancées (RFIEA). N. 10: 10-13 [Autumn 2013]

Connections: This article provides an interpretation of emerging socioecological complexity in the Amazon. Significant part of the supporting material was developed using data related to the Amazon delta area.

Eloy, L., E. S. Brondizio, and R. Pateo. In press. New perspectives on mobility, urbanisation, and resource management in Amazônia. *Bolletim of Latin American Research* (BLAR).

Connections: The article is a review article on mobility of riverine populations in the Amazon. Some of the examples used in the article came from the area under study in the Amazon delta.

Vogt, N., M. Pinedo-Vasquez, E. S. Brondizio, O. Almeida, and S. Ribero. [Accepted with revisions]. Mosaic Production Landscapes in the Amazon Estuary: Smallholder Land Use Systems, Flexibility in Land-Use Decisions and Forest Transition from WWII to Present. *Society and Natural Resources*

Connections: This article uses some of the production data assembled as part of DELTAS-DAT; however the bulk of the article relies on field research done under another project.

Tengö, M; Malmer, P; Brondizio, E; Elmqvist, T; Spierenburg, M. 2014. A Multiple Evidence Base approach to connecting diverse knowledge systems for ecosystem governance. *AMBIO.* DOI 10.1007/s13280-014-0501-3 [Published online 22 march 2014]

Connections: This article has only conceptual connections to the Deltas project, it focuses on an approach to integrate different knowledge systems as part of environmental assessment work.

*Brondizio, E. S., N. Vogt, and A. Siqueira 2013. Forest Resources, City Services: Globalization, Household Networks, and Urbanization in the Amazon estuary. In K. Morrison, S. Hetch, and C. Padoch (eds). *The Social Life of Forests.* Chicago, IL: The University of Chicago Press. Pp. 348-361.

Connections: this article was supported by another NSF-HSD project, but examines in detail one of the research sites of the Deltas project. It was revised for publication during the period of the Deltas project.

The following presentations are associated, directly or indirectly, to the project:

2014 Brondizio, E. S. Invited talk. A evolucao dos programas de mudancas ambientais globais e Future Earth Universidade de Campinas (UNICAMP), Nucleo de Estudos e Pesquisas do Ambiente (NEPAM), May 21, 2014.

Connections: Discussed the evolution of global change research program and used the example of the Belmont Forum program to illustrate the importance of interdisciplinary research. The DELTAS project was used as an example of international, interdisciplinary collaboration.

2014 Brondizio, E. S. Invited talk. Um microcosmos do antropoceno: complexidade socioambiental na Amazonia. Universidade do Vale do Paraiba (UNIVAP), Instituto de Pesquisas e Tecnologia, S. J. Campos, May 16, 2014.

Connections: This presentation starts with a conceptual discussion about the evolution of socioecological complexity in the Amazon, which is then illustrated with empirical examples from the Amazon delta region and maps produced using DELTAS-DAT.

2014 Brondizio, E. S. Invited talk. Examining land change behind the great acceleration: Examples from the Amazon. Symposium "Geosphere-Biosphere Interaction in a Future Earth", India Institute of Science, Bangalore, India, April 7, 2014.

Connections: this presentation examines reviews the history of explanation of land change in the Amazon with attention to the increasing acceleration of various types of change, including changes towards a forest transition associated with strong forest economy in the Amazon delta which was used as example.

2014 Brondizio, E. S. Invited talk. Reflections on socioecological complexity in the Amazon. Colloquium series of the Center for Latin American and Caribbean Studies (CLACS), University of Illinois Urbana-Champaign, Feb 13, 2014.

Connections: This presentation is similar to the presentation at UNIVAP discussed above.

2014 Brondizio, E. S. Invited talk. Future Earth and the Evolution of Global Environmental Change Programs. Colloquium Series, the Ostrom Workshop in Political Theory and Policy Analysis, Feb 10, 2014.

Connections: This presentation is similar to the presentation at UNICAMP discussed above.

2013 Brondizio, E. S. Invited speaker Workshop on Biodiversity and the new Sustainable Development Goals. Invited speaker [presented via telecom], Session: Values, behaviors and institutions. Talk: Institutions and conservation: fit, interplay and mismatches. Organized by UNESCO, the UN Convention on Biological Diversity, and the Heinz Center. Secretariat of the Global Environment Facility, Washington D.C., USA 17 – 19 December 2013.

Connections: used research examples from the Amazon delta derived from DELTAS-DAT about the challenges of matching administrative and institutional boundaries to biophysical systems.

2013 Vogt, N. D., K. Fernandes; M. Pinedo-Vasquez; F. Rabelo; E.J.P. da Rocha; M. Rollnic; A.S. dos Santos; E. Brondízio; O. Almeida ; S. Rivero; P.J. Deadman; Y. Dou. 2013 Linking Ethnographic and Hydro-Climate Analyses to Identify Flood Regime Changes, Their Drivers and Socio-Cultural Responses Across the Amazon Estuary. *Annual meeting of the American Geophysical Union (AGU).* Dec 10-14, 2013. San Francisco, USA. Poster: GC33A-1092.

Connections: this presentation was done as part of one of the sessions linked to the DELTAS project. It uses empirical data collected as part of the IDRC project described above (see 2. Collaborations).

University of Wurzburg

Claudia Kuenzer and Tim Funkenberg

Research Themes and Accomplishments during 2013-2014

1. Compilation of Delta datasets for trend analysis and modeling

The aim of Delta-DAT is to compile and hold observational data at a range of spatial scales to make them available for the project's consortium. Seeking out existing data sources that provide information for the three project's focus areas was the first task. Datasets that have been compiled so far are summarized in Table 1. 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.

Table 1. Data compilation

Data	Description	Region	Provider	URL
SRTM Digital Elevation Model (DEM)	DEM with a resolution of 90 m, covering the whole extent of each Delta, preprocessed with a whole filling algorithm [*Reuter*, 2007]	ARD, MRD, GBM	CGIAR-CSI	http://srtm.csi.cgiar.org
World Database on Protected Areas (WDPA)	Vector data showing all areas with a specific conservation status from Feb. 2014	ARD, MRD, GBM, Global	UNEP-WCMC	http://www.protectedplanet.net
Administrative Boundaries	Vector data including administrative boundaries of up to 4 levels	ARD, MRD, GBM	GADM	http://www.gadm.org
Dikes	Vector data showing the location of dikes in some provinces of the Mekong Delta	MRD	GFZ	http://wisdom.eoc.dlr.de/Elvis
Flood frequency Mekong Delta (ASAR-Wide Swath Mode 2007-2011)	Combination of 58 flood masks derived from ASAR radar data from the years 2007 - 2011 with a resolution of 90 m	MRD	DLR	http://wisdom.eoc.dlr.de/Elvis
Land cover classification for the Mekong Delta of 11 SPOT 5 scenes from 2009 and 2010	Land cover map including 19 classes derived from SPOT 5 satellite images with a resolution of 10 m from the year 2009 and 2010 covering large parts of the Mekong Delta	MRD	IUCN/STI	http://wisdom.eoc.dlr.de/Elvis
Land cover classification for the Mekong Delta of 13 SPOT 5 scenes from 2004 and 2005	Land cover map including 19 classes derived from SPOT 5 satellite images with a resolution of 10 m from theyear 2004 and 2005 covering large parts of the Mekong Delta	MRD	IUCN/STI	http://wisdom.eoc.dlr.de/Elvis
Land cover classification for parts of the provinces Can	Land cover map including 14 classes derived from RapidEye satellite images with a	MRD	DLR	http://wisdom.eoc.dlr.de/Elvis

Tho, Dong Thap, Vinh Long (Rapid Eye 2011)	resolution of 6.5 m from the year 2011 covering the central Mekong Delta			
Land cover map for parts of Kien Giang province 1991 LS5	Land cover map including 5 classes derived from Landsat 5 satellite images with a resolution of 30 m from the year 1991 covering the north-western part of the Mekong Delta	MRD	University of Wuerzburg	http://wisdom.eoc.dlr.de/Elvis
Land cover map for parts of the Kien Giang province 2009 LS5	Land cover map including 5 classes derived from Landsat 5 satellite images with a resolution of 30 m from the year 1991 covering the north-western part of the Mekong Delta	MRD	University of Wuerzburg	http://wisdom.eoc.dlr.de/Elvis
Time series of turbidity data	Time series of turbidity data derived from MODIS satellite images with a resolution of 500 m, data are given in gray scale values that can be transferred to Turbidity (NTU) and Total Suspended Matter (TSM)	MRD	EOMAP GmbH	http://wisdom.eoc.dlr.de/Elvis

2. Analyzing coastal morphological changes in the Amazon Estuary

The Amazon Estuary is a highly dynamic area shaped by the sediment deposits of the Amazon River coupled with a strong tidal influence. Since man-made structures, such as dams or dikes are not as dominant as in the other two focus areas (Mekong Delta, Ganges-Brahmaputra Delta) the processes of accretion and erosion are still naturally driven to a large extent. Understanding these processes is crucial to evaluate the effects of the projected construction of dams, ports and aqueducts [*GeoAmazonia*, 2009] on the natural system of the Amazon Estuary. Identifying areas that are strongly influenced by accretion or erosion is a first step to do so. These areas should reveal significant changes over time in the course of their coastline, which should be visible by comparing historical and recent satellite images to each other. For this purpose 14 Landsat satellite images from the year 1986 and 2013 (fig. 1), with preferably low cloud coverage, were downloaded from the Landsat archive. Images from the same acquisition date were merged to a single mosaic. Subsequently, each mosaic was separately classified into 35 initial classes using an unsupervised classification approach based on the ISODATA algorithm. These classes were manually merged into the three main classes: (1) land, (2) water and (3) clouds. During this process, sandbanks and mudflats were associated to the water class, since they are periodically flooded. Afterwards mosaics that belong to the same year were merged and the single classes were transformed into polygon layers. Since cloud shadows could not be distinguished from water, all water polygons totally surrounded by land polygons were associated to the land class. As a consequence water polygons that indicate lakes were also associated to the land class. But since the detection of the coastline was the priority, this fact could be neglected. Furthermore, cloud polygons were either associated to the land class, if they were totally surrounded by land polygons, or to the water class, if they were totally surrounded by water polygons. Finally, cloud polygons that were directly located above the coastline were manually edited with the help of Landsat images from the same year that do not reveal cloud cover in this specific area.

As a result two maps were generated for the year 1986 and 2013 that show the land/water distribution. Comparing the two maps with each other reveals the areas that were influenced by accretion or erosion processes (Fig. 1). Close ups of areas that are highly dynamic are shown in figure 2. In total 807.72 km² of land accreted while 788.23 km² get lost which equals an absolute gain of 19.49 km² of land due to accretion processes. Since only two dates were analyzed, it is recommended to include more time steps in order to reveal the spatiotemporal dynamic in more detail.

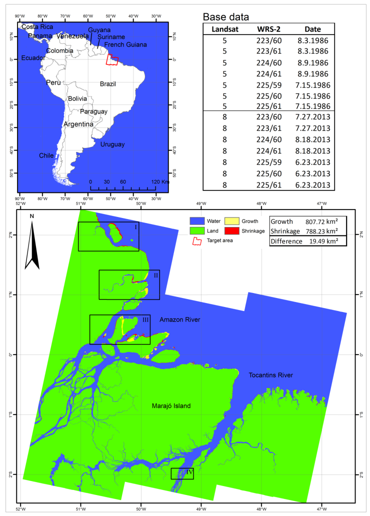

Figure 1. Changes in the course of the coastline at the Amazon Estuary derived from Landsat satellite images from 1986 and 2013.

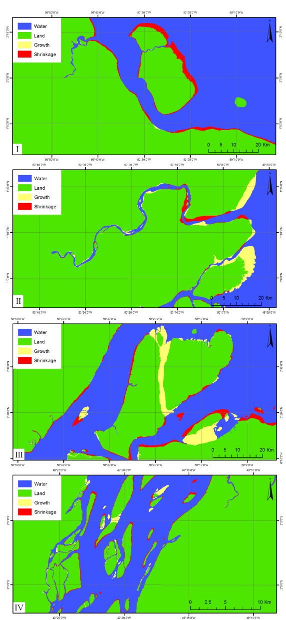

Figure 2. Close-ups from figure 1 showing changes in the course of the coastline at the Amazon Estuary comparing Landsat satellite images from 1986 and 2013.

3. Detection and filling of cloud/cloud-shadow pixel in Landsat satellite images as a preprocessing step for land cover change detection analysis

Nowadays a bunch of satellite earth observation systems scan the earth's surface on a regular basis with sensor specific ground-, spectral- and temporal-resolutions. The satellite images that are generated by these sensors can be used to derive land cover information in a spatial and temporal explicit manner that enables the detection of changes in land cover over time. Often these changes are human induced, e.g. deforestation, and provide important information for decision makers in the field of land management and nature conservation [*Nagendra et al.*, 2013]. The satellite mission with the longest continuity and therefore highly suitable for change detection analyses of the earth's surface, is the Landsat program. The Landsat program provides satellite images with a ground resolution of up to 30 m since the 1980's and operates in the optical range of the electromagnetic spectrum. Operating in the optical range has the disadvantage that clouds and their shadows are also visible in these images. Especially in tropical regions cloud coverage can be immense and need to be addressed to enable proper image analyses. This is also true for the Amazon Estuary where an almost continuous, year-round cloud coverage, caused by the vicinity to the Atlantic Ocean and the equator, occur. To reduce cloud/cloud-shadow in Landsat images a two-step method was implemented: (1) Clouds and their shadows were detected by a set of thresholds, following *Martinuzzi et al.* [2007], which was further optimized and (2) cloud/cloud-shadows in a specific base scene were filled by the prediction of new reflectance values with the help of regression tree models described in *Helmer and Ruefenacht* [2005] and *Helmer and Ruefenacht* [2007]. In figure 3 the different processing steps are shown. To implement the method a Landsat 8 image from 2013-09-27 of path 225/row 60 was chosen as base scene. This scene covers the central part of the Amazon estuary (fig. 4) and seems to be most suitable since it has the lowest cloud cover of all scenes from path 225/row 60 in the year 2013. Subsequently, two reference scenes from the same year and close to the acquisition date of the base scene were chosen to model new reflectance values for pixels in the base scene that are affected by cloud/cloud-shadow (first reference scene = Landsat 8 from 2013-09-11 of path 225/ row 60; second reference scene = Landsat 8 from 2013-10-29 of path 225/ row 60). The base scene and the two reference scenes are shown in figure 5.

At first all scenes were atmospherically corrected, using the ATCOR 2 software, to transfer the pixel values from digital numbers to surface reflectance values (visible, near infrared and shortwave infrared bands) and degree Celsius values (thermal bands), respectively. On the basis of these values two sets of thresholds were derived from the base scene to generate (1) a cloud mask and (2) a cloud-shadow mask. To detect clouds the first set of thresholds was applied to the whole scene and the resulting cloud mask was buffered by 60 meter (2 pixels) to make sure that pixels at the margin of clouds are also included. To detect cloud-shadows, the generated cloud mask was shifted to the approximate position of the cloud-shadows based on the Pythagorean Theorem, taking the sun azimuth angle and the mean distance between the clouds and their shadows into account. Since the distance between clouds and their shadows depends on cloud height, which varies within the scene, a buffer of 300 m (10 pixels) was applied. Within this buffer the second set of thresholds was used to eliminate all pixels from the cloud-shadow mask that are not affected by cloud-shadow. Subsequently a buffer of 60 m (2 pixels) was applied to the cloud-shadow mask to make sure that pixels at the margin of cloud-shadows are also included. This procedure was repeated for the two reference scenes using the same thresholds. Since these thresholds are derived from the base scene they cannot be transferred to other scenes straight forward, even though this worked well for the two reference scenes and also for the adjacent Landsat 8 scene from 2013-09-27 of path 225/row 59. For other scenes where the thresholds do not generate satisfactory results (e.g. Landsat 8 2013-06-23 path 225/ row 60), the thresholds have to be adapted or the Fmask tool could be used as an alternative. This open-source tool automatically detects cloud/cloud-shadow in Landsat images without any user interaction [*Zhu and Woodcock*, 2012]. However, Fmask was not suitable for the base scene, since many small, thin clouds and their shadows were not detected (fig. 6).

After the generation of the cloud masks and the cloud-shadow masks these data were used to (1) generate a mask including all pixel that are cloud/cloud-shadow free in both, the base scene and the specific reference scene, and to (2) generate a mask including the pixels which are clear in the specific reference scene and affected by cloud/cloud-shadow in the base scene. The former mask provides the pixel pairs that were used to train the regression tree models while the latter were used to predict new reflectance values for the cloud/cloud-shadow affected pixels in the base scene. For each spectral band a regression tree model was built with the Weka data mining software (www.cs.waikato.ac.nz/ml/weka/) embedded in IDL code. The correlation coefficients between the predicted reflectance values and the real reflectance values for each band, based on the models derived from the clear pixel pairs in the first reference scene and the base scene, are generated by a 5 fold cross-validation analysis and shown in figure 7.

Figure 8 reveals the amount of the cloud/cloud-shadow pixels in the base scene that could be modeled using the cloud/cloud-shadow free pixels in the two reference scenes. 35 % of the cloud/cloud-shadow affected pixels could be replaced by the prediction of new reflectance values using the first reference scene (Landsat 8 2013-09-11) and 25 % using the second reference scene (Landsat 8 2013-10-29). In total 60 % of the cloud/cloud-shadow pixels in the base scene could be replaced. The final result is shown in figure 9. To further reduce the cloud/cloud-shadow pixels in the base scene, it is recommended to increase the number of reference scenes.

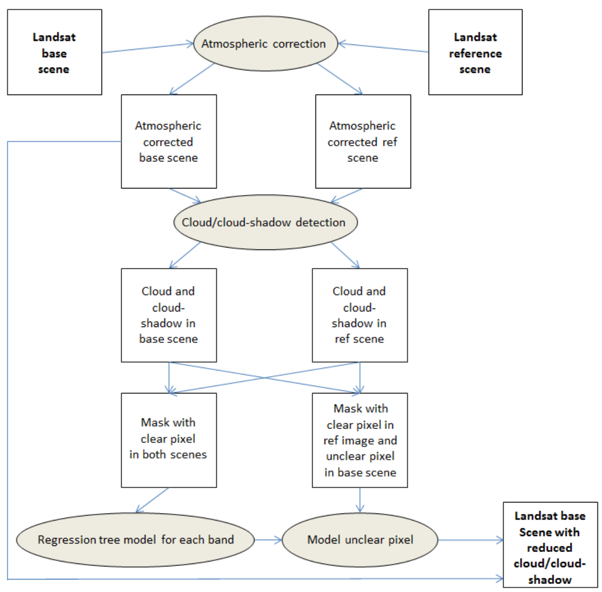

Figure 3. Flowchart showing the processing steps to detect and fill cloud/cloud-shadow affected pixel in Landsat satellite images.

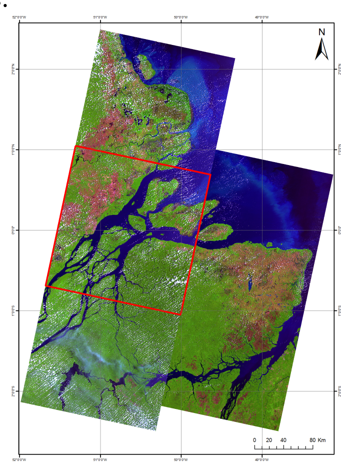

Figure 4. Amazon Estuary covered by 5 Landsat satellite images from the year 2013. The red rectangle marks the base scene from 2013-09-27 chosen for path 225/ row 60.

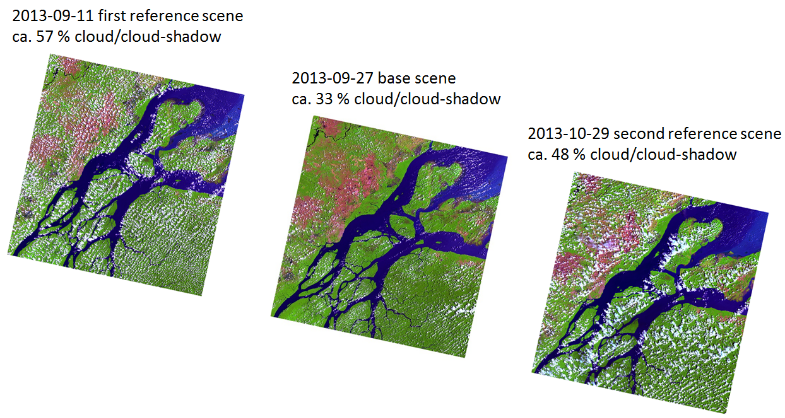

Figure 5. Base and reference scenes for path 225 /row 60 2013 used for the implementation of the cloud/cloud-shadow detection and filling method.

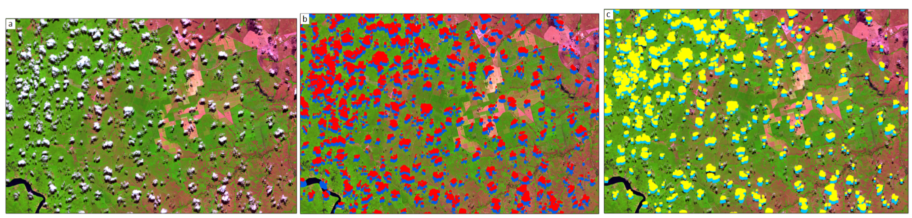

Figure 6. Comparison between cloud/cloud-shadow detection methods, (a) subset from the base scene, (b) cloud/cloud-shadow detection by thresholds (red = cloud; blue = cloud-shadow) and (c) cloud/cloud-shadow detection by Fmask (yellow = cloud; light blue = cloud-shadow).

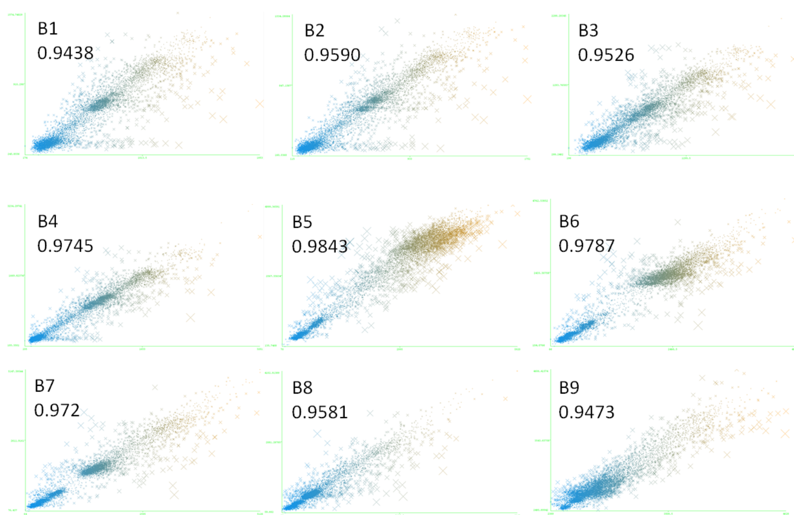

Figure 7. Correlation coefficients between the predicted reflectance values and the real reflectance values for each band, based on the models derived from the clear pixel pairs in the first reference scene and the base scene, generated by a 5 fold cross-validation analysis (X-axis = real reflectance value, Y-axis = predicted reflectance value).

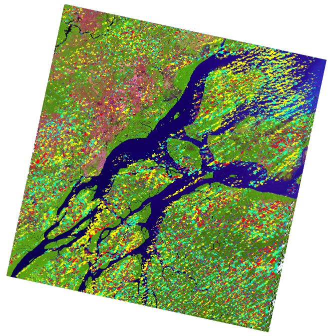

Figure 8. Base scene showing the cloud/cloud-shadow affected pixels that could be replaced by the prediction of new reflectance values, using clear pixels in the first reference scene (yellow) and the second reference scene (cyan). Pixels still affected by clouds or cloud-shadows are in red and blue, respectively.

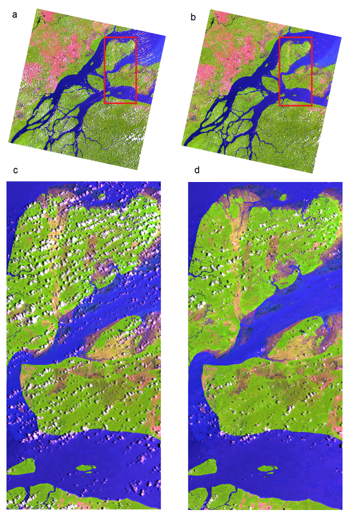

Figure 9. Final result showing the original base scene (a), the base scene with the predicted reflectance values (b), a sub set of the original base scene (c) and the same subset with the predicted reflectance values (d).

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City College of New York
Environmental CrossRoads Initiative

Research Themes and Accomplishments during 2013-2014

1. Deltas-GDVI Structured Literature Review

With colleagues in the Deltas-GDVI sub-project, we have begun a comprehensive, structured literature review focused on coastal risk and vulnerability in the three focus deltas: Mekong, Ganges, and Amazon. We have developed database search criteria and applied them at the Thomson Reuters Web of Science online database system. We also intend to include the Scopus database. Three concurrent searches were conducted with varying levels of specificity in search terms. The broadest search, included geomorphic search terms ("delta", "estuary", etc.), assessment terms ("risk", "resilience", etc.), and indicator terms ("index", "indices", etc.) returned over 13000 papers. Reducing the geomorphic terms search from abstract to title reduces the set to approximately 3400 papers. Finally, including specific delta terms ("Mekong", "Ganges", etc.) reduces the search to 87 papers. We intend to divide the smallest section and a sampling of the mid-range set among members of the team for analysis.
The structured analysis phase will entail coding each research paper by delta, risk framework used, time period of the assessment, the outcome of the assessment, risk indicators considered in the assessment, type, origin, scale, and quality of data, and any specific limitations of the study. This phase of the study is ongoing.

2. Environmental Stress and Vulnerability analysis for deltas

By assembling datasets of global scope with known impacts on the delta system, we can identify systems under stress in a relative manner without imposing specific process models or specifying exact metrics of risk. This heuristic method is used to make quantitative, objective, and replicable estimates of delta stress across diverse scales, and the resulting indices can be traced in time. Selected stress variables are each directly or indirectly indicative of changes to important deltaic processes affecting the biogeochemical delta environment.

Included stress indicator variables are population density in the delta and in the upstream basin, an indirect measure of development and land use change; estimated artificial reservoir volume in the upstream basin, normalized by mean river discharge, a measure of sediment trapping; wetland disconnectivity in the delta and upstream basin, a measure of agricultural conversion of former wetlands; impervious surface fraction in the upstream basin and delta, an indicator of development of natural landcover; estimated delta groundwater abstraction in excess of recharge, a major component of accelerated delta land subsidence; and a petroleum extraction flag indicting presence of extraction anywhere in the delta, an additional component of accelerated delta land subsidence.

Figure 1 shows the environmental stress characteristics of the Mekong, Ganges, and Amazon deltas. These values are rank-normalized relative to 48 global deltas to reduce the influence of outlier deltas, important given the wide range of scales among these systems. These three deltas are substantially different: the Amazon is clearly the least environmentally stressed, with relatively low population density in the delta and the upstream river basin, few large reservoirs relative to the discharge of the Amazon River, and very low development, indicated by impervious surface area and wetland disconnectivity. The Mekong, in contrast, has moderate levels of urbanization and agricultural development, somewhat more impact from upstream dams and reservoirs, and much greater population density in the delta and upstream watershed. Finally, the Ganges is the most stressed of these systems, with very high population densities, high urbanization and wetland disconnectivity, moderate upstream dams and reservoirs, and the presence of petroleum extraction from delta sediments.

Figure 2 shows how the Mekong, Ganges, and Amazon environmental stress directly compare in aggregate to the other deltas in the sample. The Ganges is the highest ranked, the Mekong is near the middle, and the Amazon is one of the least stressed systems.
Additional work is ongoing on this project to relate our environmental stress estimates to broader projections of risk to coastal populations by considering the frequency and magnitude of hydrological hazards such as fluvial floods and tropical cyclones, and the vulnerability of particular communities on the coast.

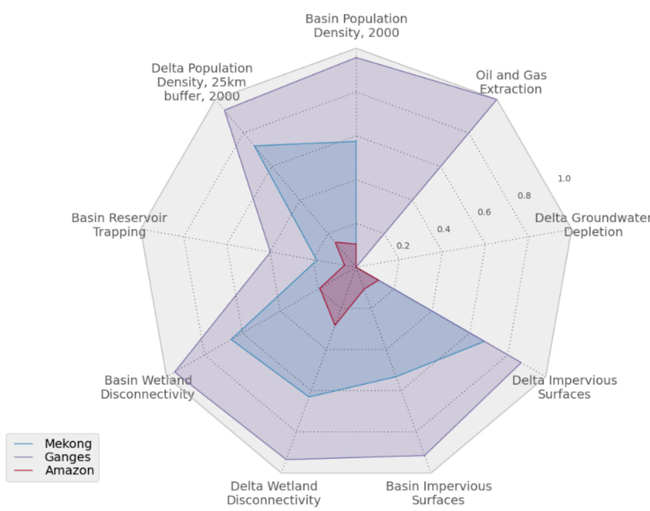

Figure 1. Environmental characteristics of the Mekong (blue), Ganges (purple), and Amazon (red) deltas. Values are rank-normalized relative to 48 global deltas. A value of 1 indicates the delta is the highest among all deltas for a given indicator, while 0 indicates it is the lowest delta.

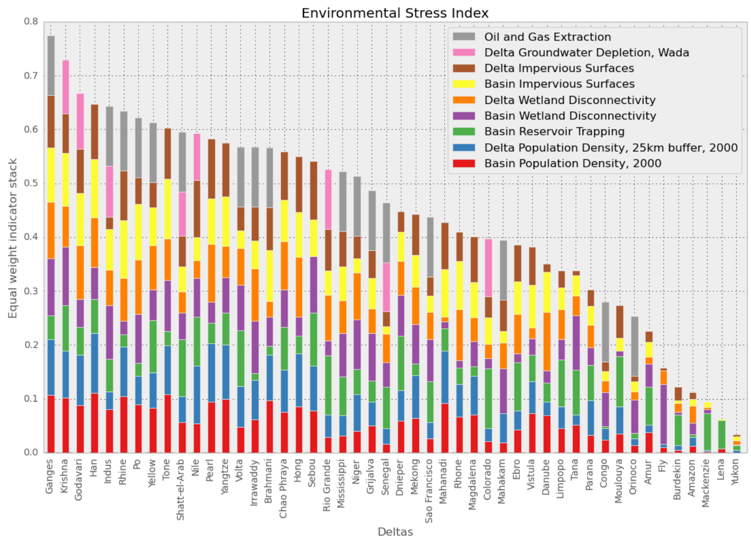

Figure 2. Ranking of all deltas in the database based on their aggregate environmental stress index. Indicators are equally weighted. The Ganges is the highest ranked, the Mekong is near the middle, and the Amazon is one of the least stressed systems.

3. Precipitation and surface inundation patterns in delta systems

Hydrologic changes in river delta systems occur over a broad range of time scales, from hours (tides), to decades (urban development), to millennia (river bank avulsion). 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.

Surface inundation is obtained from a new microwave-radar based global time-series, SSWAMPS (Satellite Surface Water Microwave Product Series). We have conducted a spatial analysis of dominant inundation modes for the Amazon, Ganges, and Mekong deltas using Empirical Orthogonal Function analysis (Principal Component Analysis). Early results showing the dominant mode of inundation are in Figures 3-5. The first mode for these three deltas is strongly associated with an annual signal. For instance, in the Mekong, the coastal areas become relatively wet while the upper Mekong delta becomes relatively dry, during the monsoonal, high river discharge period between January and August. This is consistent with the large areas in this region used for rice cultivation, and irrigated with diversions from the Mekong River.

Work is ongoing to compare this inundation data with rainfall estimated using an improved detection algorithm based on TRMM (Tropical Rainfall Measuring Mission) data.

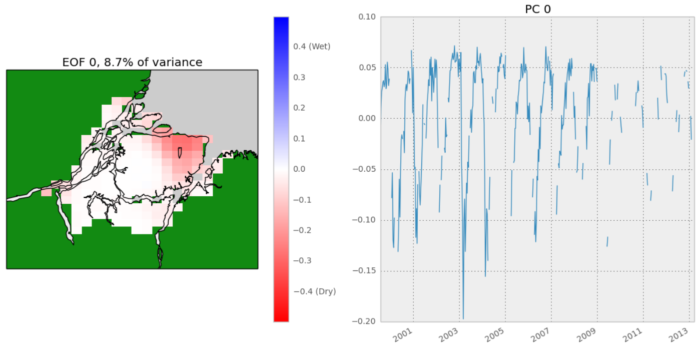

Figure 3. Amazon first EOF (left) and associated principal component (right).

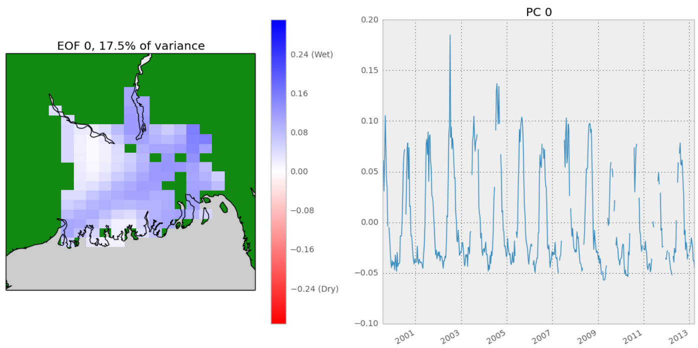

Figure 4. Ganges first EOF (left) and associated principal component (right).

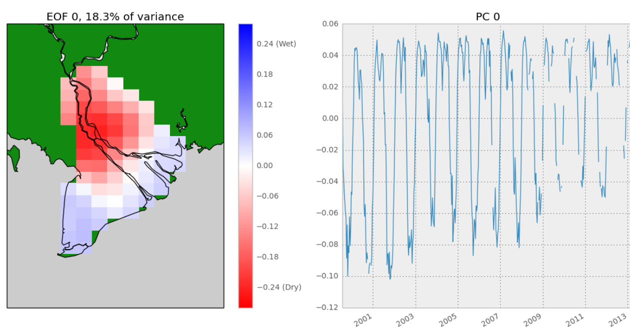

Figure 5. Mekong first EOF (left) and associated principal component (right).

4. Design and configuration of the Deltas-DAT data service

The team at CUNY Environmental CrossRoads Initiative has designed and implemented a plan for a shared, and potentially distributed, data storage and distribution system. The main design goals were:

1. *Data type agnostic:* The system must hold heterogenous data, including raster and vector GIS data, remote sensing imagery, spreadsheets, text files, etc…
2. *Access controlled:* Stored data may have distribution restrictions based on provenance or research status
3. *Expandable storage:* Physical storage volumes should be able to be added to system as needed

4. *Distributed:* Given that this project is an international collaboration, the ability for multiple institutions to host dataset has several practical benefits, including cost sharing and network latency minimization
5. *Reliable:* This will be the authoritative data storage for the Belmont-Forum DELTAS project, and as such should be easily backed-up or replicated.

In light of these needs, we chose the iRODS Data Management middleware. This software suite provides a data catalog database that users interact with to store and retrieve data from any number of physical storage systems. The CUNY Environmental CrossRoads team is hosting the data catalog that defines the DELTAS iROD data grid. Currently there is one data server providing a physical storage resource, also hosted at CUNY. All access to this data is via the iRODS data grid server, which is accessible to the Belmont-Forum DELTAS team.
We have hosted one online training workshop to introduce members of the research team to the use of the iRODS system. Based on feedback and need over the course of the project, we will consider deploying additional physical storage resources on other institutional campuses to increase available storage space and reduce network latency involved in storing and retrieving data.

Future Research 2014-2015:

1. EOF/PC analysis of TRMM rainfall over the Mekong, Ganges, and Amazon Deltas, for comparison of spatial modes with inundation
2. 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. and C.J. Vörösmarty (in preparation). A Global Deltas Typology of Environmental Stress and Coastal Hazard.

Tessler, Z.D., C.J. Vörösmarty, E. Foufoula-Georgiou, A. 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.

C.J. Vörösmarty, E. Foufoula-Georgiou, Z.D. Tessler, I. Overeem, et al. (2014). Environmental CrossRoads and a New Global DELTAS Sustainability Initiative. Deltares, Delft, Netherlands, 9 January 2014.

Tessler, Z.D. and C.J. Vörösmarty (2013). A Global Deltas Typology of Environmental Stress and its Relation to Terrestrial Hydrology. EP34B-02, AGU Fall Meeting, San Francisco, CA, 9-13 December 2013.

Workshops

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.

Fabrice Renaud and Zita Sebesvari

Research Themes and Accomplishments during 2013-2014

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

To be of particular use to policy-makers, vulnerability metrics need to be developed based on indicators that are quantifiable at the sub-regional scale and transferable to different delta contexts. Policy factors which are critical in shaping future development of various delta environments, but also differ among various governance regimes, are often ignored in assessing delta vulnerability and need to be incorporated in vulnerability metrics. Emphasis also needs to be placed on capturing the interface between ecosystems and social systems through understanding and quantifying delta ecosystem services and how these can be altered by external (e.g., environmental hazards) and internal factors (e.g., induced by policy decisions).

Activities

The team at UNU-EHS (Dr Fabrice Renaud (PI) and Dr Zita Sebesvari) started with the execution of the project beginning of October 2013. The activities are linked to the work plan established for the GDVI project component:

1) Selection and adaptation of a theoretical framework
2) Identification and evaluation of a preliminary set of indicators

1. Selection and adaptation of a theoretical framework for delta resilience and vulnerability

The selection and adaptation of the theoretical framework is an iterative process which triggers and accompanies the first research steps as well as undergoes modification in the course of the research. As a point of departure the research team selected the SUST framework modified by Damm (UNU-EHS) (Figure 1). The framework suggests a systemic approach to consider processes and characteristics of social-ecological systems (SESs) and understands vulnerability as a composition of exposure, susceptibility, and capacities. Drivers and causes are shown on the left side of the framework while the right side considers the impacts/consequences. Vulnerability is dynamic and changes over time and place. Thus, the framework considers place-based as well as cross-scale ecological and social processes. Elements exposed to hazards are humans, assets, and ecosystems. Susceptibility is defined as the condition or rate of response of the SES to all perturbations and stresses within the system. Capacities are the ability of a system to resist, cope with, and adapt to a certain hazard. The adaptation of the framework is underway. The modified SUST framework was used in the first regional consultation in Ho Chi Minh City, Vietnam. The experiences and insights generated in this consultation process are currently used to modify the framework.

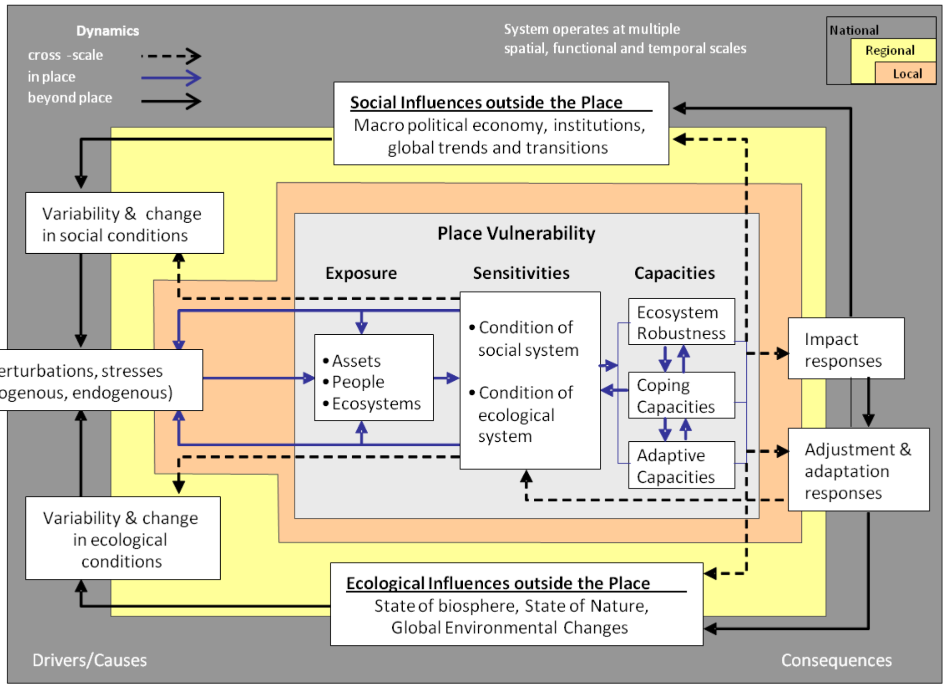

Figure 1. Modified SUST framework. Based on *Turner et al.* [2003] modified by *Damm* [2010].

2. Identification and evaluation of a preliminary set of indicators for delta vulnerability assessment

Given the complexity of SESs, the in-depth assessment of vulnerability requires a structuring and reduction of available data to a set of suitable and well-chosen indicators that facilitate an assessment of vulnerability. The selection is a multiple tier process which is to be executed for all three model deltas leading at the end to a generalized set of indicators applicable worldwide.

1) Overview of potential hazards, impacts, 'susceptibility', 'capacities'
2) Review of frequently used environmental indicator approaches
3) Development of vulnerability categories
4) Preliminary indicator list
5) Evaluation of indicators
6) Final indicator list

In the reporting period we mainly focused on activities 1) and 2) but also made progress on 3) and 4) specifically for the Mekong Delta. We conducted a structured literature search for all 3 model deltas to characterize potential hazards, impacts, 'susceptibility', 'capacities' and work to review frequently used vulnerability assessment methods as well as environmental indicator approaches together with project partners in the frame of fast track paper No. 4.

Additionally, an expert consultation was organized in Ho Chi Minh City, Vietnam to serve to first 4 steps of the indicator development for the Mekong Delta (i) Overview of potential hazards, impacts, 'susceptibility', 'capacities'; ii) Review of frequently used environmental indicator approaches; iii) Development of vulnerability categories; iv) Preliminary indicator list).

3. BF-DELTAS expert consultations on delta vulnerability indicator selection – Mekong Delta, 2-3 April 2014, Ho Chi Minh City, Vietnam

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. It also provided an opportunity to begin with the development of a delta vulnerability index applicable for the Mekong Delta at the sub-delta level by integrating social and ecological elements and first judgments on data quality accessibility. As vulnerability methodologies and indices are a function of different factors (vulnerability of whom to what), the workshop 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.

Organizers and participants

The consultation was co-organized by two DELTAS project partners

1) the United Nations University, Institute for Environment and Human Security (UNU-EHS) – the project partner responsible for the project component Global Delta Vulnerability Index (GDVI) represented by Dr. Fabrice Renaud, Dr. Zita Sebesvari Dr. Le Thi Thu Huong, and
2) the HCMC Institute of Resources Geography (HCMCIRG), Vietnam Academy of Science and Technology (VAST) – the national project partner of DELTAS in Vietnam – represented by Assoc. Prof. Dr. Nguyen Van Lap and Assoc. Prof. Dr. Ta Thi Kim Oanh.

The selection of participants followed an inclusive approach: representatives from provincial level authorities, scientific organizations, NGOs, independent consultants, and DELTAS project partners were invited. Annex 1 lists the participants including their affiliation.

Agenda of the meeting

The agenda was designed to support the participative character of the consultation. Thus, the organizers provided an input presentation only. The meeting was mainly structured around the following agenda items:

1) "Mapping" the hazard landscape: delta sub-regions and relevant hazards
2) Development of Impact Diagrams for selected hazards on local and national scale
3) Modified SUST framework for vulnerability assessment
4) Selection of indicators to characterize the vulnerability of systems with respect to the identified hazards

All agenda items followed the same structure: short input presentation by Fabrice Renaud or Zita Sebesvari followed by group work and a plenary discussion. Annex 2 refers to the detailed agenda of the meeting.

The workshop yielded a preliminarily list of hazards on the sub-delta levels as well as a set of preliminarily indicators to characterize vulnerability to floods (upper delta), enhanced variability in river discharge and associated droughts (middle delta) and coastal erosion paired with salinity intrusion (coastal zone). Figure 2 refers to the delta hazards identified by one of the working groups. Table 1 shows the translation of an impact diagram of floods developed by the participants while Table 2 shows examples of potential indicators. The indicators shown are related to high flood as hazard and to the vulnerability sub-component `exposure´ in the Upper Delta.

TYPE	KEY DRIVERS
coastal erosion	big waves with high amplitude high water level coastal currents human activities such as deforestation, land use change, groundwater exploitation, sand exploitation soil subsidence sea dikes
saline intrusion	high waves, high tides human activities such as aquaculture, agriculture
storm + high waves	natural processes
high tides	strong winds, sea level rise
temperature rise	global warming deforestation
Subsidence	natural subsidence human activities such as groundwater exploitation, urbanization, hydropower development
Flood	forest losses from upland areas dike systems
unusual rainfall	climate change
high waves	natural processes
drought	temperature rise deforestation, high water evaporation
thunderstorms, cyclones	natural processes

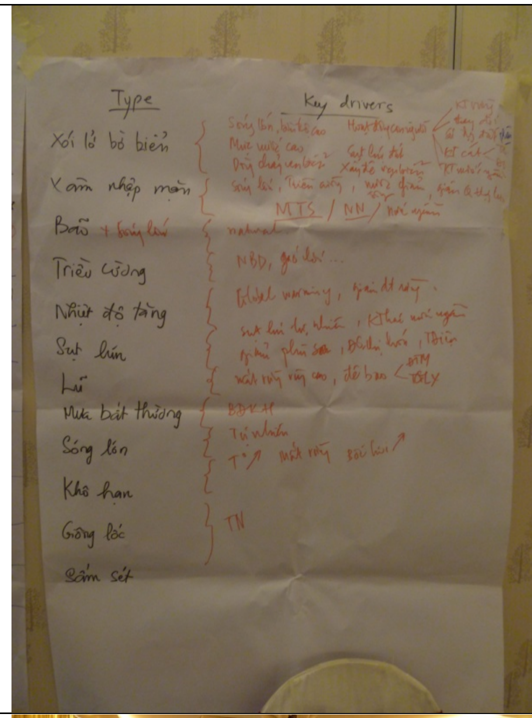

Figure 2. Hazards identified by the Upper Delta Group.

Table 1. Translation of the impact diagram developed by the Upper Delta Group related to floods.

<table>
<tr><td rowspan="13">->
High flood</td><td rowspan="2">-> water pollution</td><td>-> cost for water treatment</td><td></td><td></td><td rowspan="12">->
impact on household income and to regional economy</td></tr>
<tr><td>-> human and animal health</td><td>-> cost for disease treatment</td><td></td></tr>
<tr><td rowspan="2">-> erosion (river bank canal bank)</td><td>-> land loss</td><td></td><td></td></tr>
<tr><td>-> loss of soil organisms</td><td></td><td></td></tr>
<tr><td rowspan="9">-> inundation</td><td>-> damages on infrastructures</td><td></td><td></td></tr>
<tr><td>-> decrease of productions</td><td></td><td></td></tr>
<tr><td>> cost to build infrastructures for resettlement</td><td></td><td></td></tr>
<tr><td>-> cost to build stilt houses</td><td></td><td></td></tr>
<tr><td>-> difficult for education, transportation, medical services</td><td></td><td></td></tr>
<tr><td rowspan="4">-> cost to build dike systems</td><td rowspan="4">-> dike related problems</td><td>-> dike breakage</td></tr>
<tr><td>-> loss of silt</td></tr>
<tr><td>-> increase of water flow, water pressure to both upper and lower zones</td></tr>
<tr><td>-> loss of aquaculture production</td><td>-> migration</td></tr>
</table>

Table 2. Examples of potential indicators developed by the consultation group. The indicators shown are related to high flood as hazard and to the vulnerability sub-component `exposure´ in the Upper Delta.

HAZARD: HIGH FLOOD

Components	Sub-Comp	Indicators	Data Source and type
Exposure	*People*	% Dân số sống trong vùng lũ (% population in the flooded zone)	Niên giám thống kê (GSO) (sách)/DARD báo cáo hàng năm (annual report, DARD)
	Asset	% Diện tích cây trồng trong vùng lũ (% production land in the flooded zone)	DARD báo cáo hàng năm (annual report, DARD)
		% Vật nuôi trong vùng lũ (% animal in the flooded zone)	DARD báo cáo hàng năm (annua report DARD)
		% CSHT (Điện, đường trường, trạm, công trình thủy lợi) (% infrastructure (electricity supply, schools, stations, irrigation systems) located in the flooded zone)	Niên giám thống kê (GSO)/ủy ban nhân dân huyện (People committee)
	ES		

Next steps

The indicators will be further validated, assessed, and data will be gathered. Information and views from participating stakeholders will feed into the side event "Science-to-Action: Aligning science with stakeholder and community needs in the Mekong Delta system" the Rotterdam International Conference 2014, Deltas in Times of Climate Change II (24-26 September 2014). This event will link stakeholders and policymakers at the local and regional scales with scientists to identify key informational needs and knowledge gaps in the Mekong Delta and to co-design a research strategy to improve the reliability and access to such information. The second stakeholder consultation will take place in Bangladesh end of August.

Related publications

Damm, M. 2010. Mapping social-ecological vulnerability to flooding. A sub-national approach to Germany. Graduate Research Series, Vol. 3, UNU-EHS, Bonn

Renaud, F.G., Huong, T.T.L., Lindener, C., Guong, V.T., Sebesvari, Z. (2014) Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. Climatic Change. DOI 10.1007/s10584-014-1113-4.

Renaud F.G., Syvitski J.P.M., Sebesvari Z., Werners S.E., Kremer H., Kuenzer C., Ramesh R., Jeuken A., Friedrich J. (2013). Tipping from the Holocene to the Anthropocene: how threatened are major world deltas? Current Opinion in Environmental Sustainability 5, 644-654.

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Turner, B.L. II., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A. (2010). A framework for vulnerability analysis in sustainability science. PNAS 100, 8074-8079.

Contribution to the Rotterdam International Conference 2014, Deltas in Times of Climate Change II (24-26 September 2014)

Oral presentation on "Global delta vulnerability indicator development" by Fabrice Renaud, Zita Sebesvari, Nguyen Van Lap

1 presentation in the session Science-to-Action: Aligning science with stakeholder and community needs in the Mekong Delta system

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Steven Goodbred Jr. and Carol Wilson

With contributions from Irina Overeem, Kimberly Rogers, Michael Steckler

Research Themes and Accomplishments during 2013-2014

Research in Year 1 on the BF-Deltas project has centered on identifying the key issues and regions associated with vulnerability and change in the Ganges-Brahmaputra River (GB) delta, Bangladesh. The G-B delta, with 150 million people and a vast, low-lying coastal plain, is perceived to be at great risk to increased flooding and submergence under multiple sea-level rise scenarios. Although these risks are widely recognized, our scientific understanding of the local conditions and processes within this, and other, complex deltaic landscapes is incomplete. For example, if we consider the G-B delta as a single unit, then effective dispersal of the river's one megaton of sediment across the 150 million km^2 of terrestrial and marine delta can account for ~0.5 cm/yr of sediment aggradation, which is roughly equivalent to the rate of relative sea-level (RSL) rise measured at several of the area's tide gauges. In reality, though, rates of sedimentation are not evenly distributed across the delta; nor are rates of RSL change due to differences in subsidence, compaction, and alterations of the channels and tidal regime. Understanding these local patterns and controls are essential to effective and realistic management of these regions. These are the topics on which we are directing our focus and contributing to the modeling efforts and risk assessments being conducted by the larger DELTAS research community funded under NSF Belmont Forum-G8 Collaborative Research

1. Ganges-Brahmaputra River (GB) Delta Tidal Channel Processes

Observational data from two tidal channel CTD deployments yielded water level, salinity (in the form of electrical conductivity), and temperature over a 12-month time interval. One CTD was located on the Dhaki River, which is a connecting channel confined by embanked polders between the Shibsa and Rhubsa Rivers. This CTD recorded data from May until October 2012, capturing the daily semi-diurnal tidal fluctuation and decrease in salinity of channel waters during the monsoon wet season. Another CTD was deployed in a smaller tidal channel near the Bhadra River that feeds the mangrove intertidal platform (part of the northern Sundarbans forest). This CTD was deployed from March 2012 until February 2013, also capturing the daily semi-diurnal tidal fluctuation and decrease in salinity over the monsoon. Comparison of the two data sets (Fig 1) reveals that the Dhaki River exhibits an ebb-dominated tidal asymmetry, while the Sundarbans channel site is flood-dominated. There is a 1-2 hour delay between the tides at the two sites, which can be accounted for by frictional forces along the channel lengths, though this appears to be most pronounced during the spring tides. The timing and duration of the monsoon freshening is also very different between the two sites. Tidal waters in the Dhakai River (which is well connected to Shibsa and Rhubsa Rivers) freshen gradually between June 15 and July 15 (corresponding to the timing of the monsoon discharge along the Padma River and presumably the freshwater plume offshore). This record shows a gradual increase in salinity beginning late

August-early September. In contrast, there are step-wise decreases in salinity at the Sundarbans tidal channel (occurring ~June 3 and August 2). These tidal channels become fresh later than that of the Dhaki, but remain fresh longer (until November). This suggests that there is a groundwater discharge component in this region during this time frame, however further analyses are needed to confirm this hypothesis.

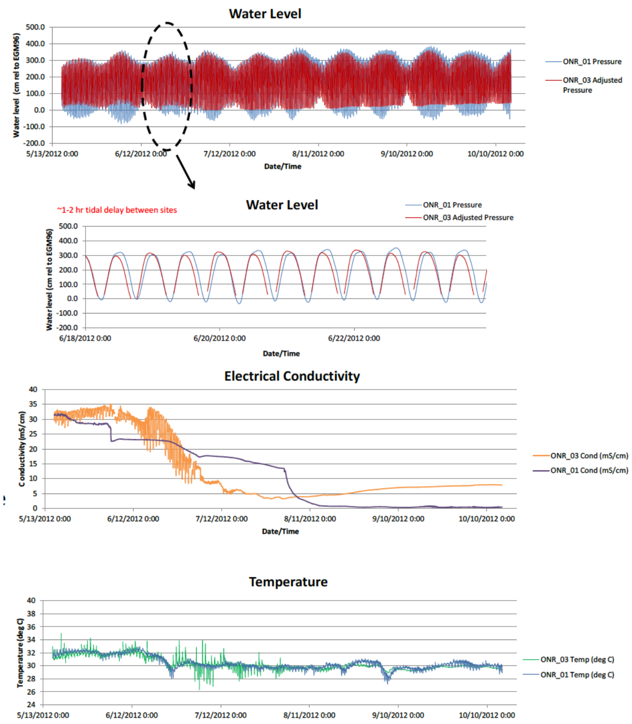

Figure 1. Water level, salinity, and temperature records collected from March 2012 to May 2013 from the tidal delta plain of Bangladesh.

2. Tide Wave Evolution and Tidal Harmonics on the GB Delta Plain

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 cutoff 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 this case, a critical understanding of the tidal regime and its spatial and temporal variations becomes key to anticipating how the region will evolve with continued global environmental change and local human manipulations of the physical landscape. Here we have performed a harmonic analysis on the water level records mentioned above using the World Tides program (courtesy of J. Boon; Fig 2). The tidal constituents found common to all analyses included: O1, K1, N2, M2, S2, MU2, M4, MS4, K2, L2, MN4, 2MK3, 2MS6; with the most dominant constituent being the M2 with an average amplitude of ~1.4 (Table 1). Particularly useful are the residual terms, which reflect local scale non-linearities in the tidal excursion. Such deviations reflect asymmetries in tidal transport that directly impact sediment flux terms. We are currently evaluating where such asymmetries develop and investigating their control on sedimentation patterns on the landscape.

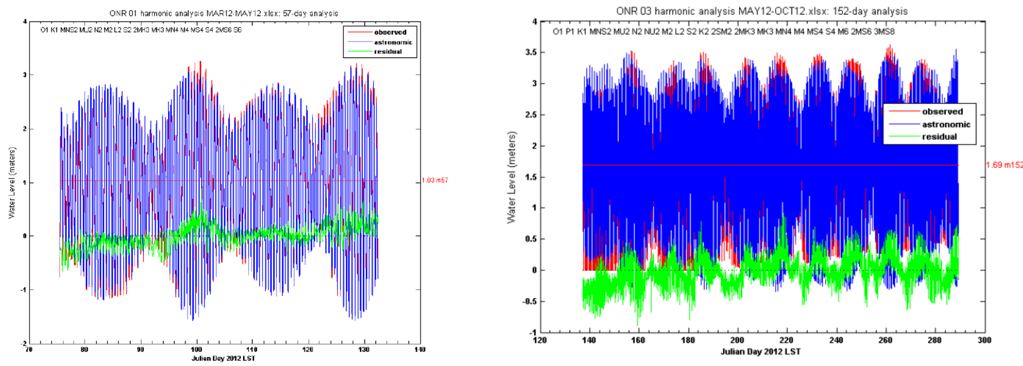

Figure 2. Representative harmonic analysis of water-level records using World Tides program (J. Boon) and collected by CTDs deployed March to May 2013 and May to October 2012.

Table 1. Amplitude and phase results for tidal constituents determined during each deployment period using the World Tides program (J. Boon).

ONR_01

Mar'12 to May '12

Stage IV.	O1	K1	N2	M2	S2	M4	MS4	L2	MU2	K2	MK3	MN4	2MS6	MNS2	2MK3	S4	S6	RMS	%R_Var
amplitude	0.072	0.146	0.363	1.492	0.578	0.109	0.109	0.121	0.081	0.202	0.037	0.055	0.041	0.064	0.034	0.029	0.004	0.187	97.750
phase	325.00	4.03	218.78	307.58	59.52	88.94	185.56	286.82	343.27	215.01	85.74	359.13	70.2	274.73	112.19	293.51	293.25		

May'12 to Oct '12

Stage V.	O1	K1	N2	M2	S2	MU2	K2	M4	MS4	L2	P1	2MK3	MN4	NU2	2SM2	MK3	S4	LAM2	2MS6	RMS	%R_Var
amplitude	0.078	0.154	0.271	1.463	0.541	0.181	0.162	0.173	0.164	0.089	0.052	0.048	0.069	0.075	0.051	0.050	0.039	0.058	0.036	0.244	95.870
phase	326.78	17.95	220.77	308.63	57.60	339.93	216.74	88.39	194.71	294.56	46.83	92.51	357.74	296.42	317.60	146.39	325.63	83.87	47.26		

Oct'12 to Feb '13

Stage V.	O1	K1	N2	M2	S2	MU2	K2	M4	MS4	L2	P1	NU2	MK3	MN4	2MS6	MNS2	2MK3	M6	RMS	%R_Var
amplitude	0.078	0.170	0.268	1.460	0.577	0.113	0.155	0.085	0.078	0.101	0.063	0.095	0.035	0.043	0.031	0.032	0.033	0.021	0.208	96.870
phase	320.01	15.21	219.40	309.31	53.57	334.33	219.37	92.58	192.07	298.23	27.73	310.35	139.02	354.14	66.25	242.32	92.97	327.80		

Mar'12 to Feb'13

Stage I	O1	K1	N2	M2	S2						RMS	%R_Var
amplitude	0.760	0.151	0.273	1.473	0.562						0.422	88.03
phase	326.57	16.90	219.68	308.89	56.19							

May'12 to Feb'13

Stage IV.	O1	K1	N2	M2	S2	MU2	M4	MS4	K2	L2	M1	NU2	MN4	2MK3	2MS6	P1	2N2	LAM2		RMS	%R_Var
amplitude	0.078	0.162	0.275	1.459	0.557	0.154	0.136	0.128	0.155	0.086	0.013	0.085	0.058	0.041	0.033	0.058	0.058	0.051		0.250	95.600
phase	323.97	15.61	220.82	308.95	55.80	342.31	89.47	194.12	219.72	293.21	183.37	301.00	357.86	92.31	54.61	39.09	60.59	90.99			

ONR_03

Stage IV.	O1	K1	N2	M2	S2	MU2	K2	M4	MS4	L2	2MK3	MN4	2MS6	3MS8	P1	MNS2	NU2	2SM2	MK3	S4	M6
amplitude	0.078	0.140	0.236	1.380	0.479	0.180	0.128	0.110	0.100	0.076	0.045	0.041	0.066	0.030	0.053	0.036	0.068	0.051	0.037	0.027	0.037
phase	135.33	179.29	209.53	291.74	27.13	350.79	180.37	83.93	184.84	283.75	251.58	356.99	67.40	216.36	207.70	289.57	290.87	286.19	309.48	299.53	338.33

3. Natural and Human-Induced Changes in GB Tidal Channel Network

Linked with tide wave propagation and deformation across the delta plain is the tidal channel network that conveys the water and associated suspended sediment. 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. Here we have begun an analysis of historical Landsat imagery that shows a decrease in drainage density of the intertidal platforms of southwest Bangladesh due to the widespread contruction of embankments (polders), mostly through the closure/restriction of primary creeks (Fig 3). Many infilling channels are also observed, where much of this new land is cultivated for shrimp production. In contrast, preliminary results show the tidal channel network in the Sundarbans forest is relatively stable by comparison (Fig 3 and Table 2). The reduced connectivity of the tidal channel network in embanked areas and how this impacts associated hydrodynamics will be the focus of future analyses.

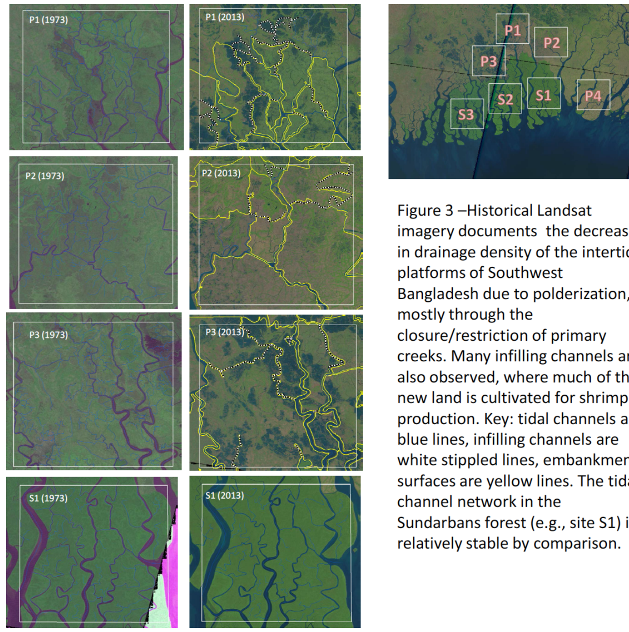

Figure 3 –Historical Landsat imagery documents the decrease in drainage density of the intertidal platforms of Southwest Bangladesh due to polderization, mostly through the closure/restriction of primary creeks. Many infilling channels are also observed, where much of this new land is cultivated for shrimp production. Key: tidal channels are blue lines, infilling channels are white stippled lines, embankment surfaces are yellow lines. The tidal channel network in the Sundarbans forest (e.g., site S1) is relatively stable by comparison.

Table 2. Preliminary GIS results of changes in tidal creek length and calculated drainage density (D) from historical satellite imagery.

	POLDERED AREA		NATURAL AREA	
	1973*	2003	1973*	2003
Total creek length (km)	536	391	495	510
Ghas shrimp creek length (km)	0	106	N.A.	N.A.
Mean width of ghas shrimp creeks (m)	276 ± 91	25 ± 11	N.A.	N.A.
Non-shrimping creek length (km)	536	284	495	510
Drainage density, D	0.48	0.25	0.44	0.45
CHANGE IN D		-47%		3%

4. Flood Risk in Natural and Embanked Landscapes of GB delta plain

To understand the impacts of human alteration of the delta, we compare land-surface elevations between the GB delta's pristine Sundarbans mangrove forest and the adjacent embanked (poldered) agricultural landscape. The Sundarbans is known to have remained largely stable through recent and late Holocene times, sustained by a network of fluvial and tidal channels that effectively disperse the immense riverine sediment load. However, we document nearby human-altered landscapes in southwest Bangladesh that have not fared as well, experiencing a net elevation loss of 1.0-1.5 m since being embanked in the 1960s. This elevation offset is a result of decreased sedimentation, accelerated compaction, and loss in belowground biomass. The acute effects of this elevation loss were demonstrated in 2009 when the embankments of several large islands failed during Cyclone Aila, leaving large areas of land tidally inundated for up to two years until embankments were repaired. Despite sustained human suffering during this time, the newly reconnected landscape received tens of centimeters of tidally deposited sediment that accounted for several decades' worth of normal sedimentation. Although many areas still lie well below mean high water and are at considerable risk of severe flooding, observations here demonstrate that elevation recovery may be possible using a management strategy of controlled embankment breaches.

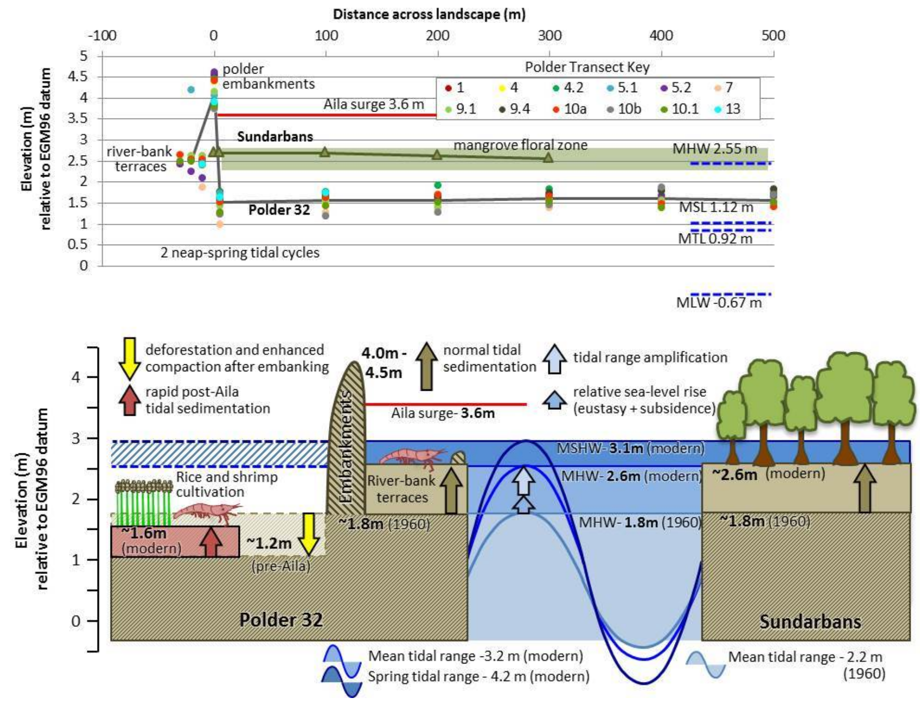

Figure 4. Results of the GPS elevation survey (Polder 32 transects in colored circles; Sundarbans transects in black triangles) and spring-neap tidal cycles (gray line), along with a conceptual model of the poldered and natural landscapes. The Sundarbans platform and river terraces outboard of Polder 32 are positioned at +2.65 m relative to EGM96 datum and flood during spring high tides. Polder embankment elevations range from +3.7 to +4.6 m. The poldered landscape is positioned at +1.5 m and, in the absence of embankment protection, is flooded at every high tide.

Future Research (2014–2015)

In the next year we will continue our observations and database development as described for the Year 1 activities. In particular, we will seek to incorporate our results and findings into the Risk Analysis and other portions of the BF-DELTAS project. We will also begin one new line work as described below:

1. Observations of Dynamic Surface Elevation

We have recently deployed SET (Surface Elevation Tables) at two locations on the GB tidal delta plain. These SET instruments will be monitored four times during the year to get precise measurements of sedimentation, compaction, ground swell, and flooding depth and hydroperiod. Data will be integrated with the more regional observations of tide-wave and channel-network analyses begun in Year 1.

Publications 2013-2014 (partially funded by this grant)

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Reitz, M.D., Pickering, J.L., Goodbred, S.L., Paola, C., Steckler, M., and Seeber, L., In review. Effects of tectonic deformation and sea level on river path selection: theory and application to Bangladesh. Submitted to Journal of Geophysical Research – Earth Surface.

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Conference presentations and abstracts:

Goodbred, SL, Auerbach, LW, Wilson, C, Gilligan, JM, Roy, K., Ahmed, KR, Steckler, MS, Nooner, S., 2013. A Tale of Two Deltas: Contrasting Perspectives on the State of Natural and Human-modified Regions of the Ganges-Brahmaputra River Delta American Geophysical Union, Annual Meeting. San Francisco, CA. Dec. 9-13 (Invited).

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Wilson, C, Goodbred, SL, Auerbach, LW, Ahmed, KR, Paola, C, Reitz, MD, *Pickering, J., 2013. Geomorphology and Landscape Evolution Model for the natural and human-impacted regions of the Ganges-Brahmaputra-Meghna Delta. American Geophysical Union, Annual Meeting. San Francisco, CA. Dec. 9-13.

Sincavage, R, Goodbred, SL, Williams, LA, Pickering, J, Wilson, C, Steckler, MS, Seeber, L, Reitz, MD, Hossain, S, Akhter, SH, Mondal, DR, Paola, C, 2013. A comprehensive view of Late Quaternary fluvial sediments and stratal architecture in a tectonically active basin: Influence of eustasy, climate, and tectonics on the Bengal Basin and Brahmaputra River system. American Geophysical Union, Annual Meeting. San Francisco, CA. Dec. 9-13.

Goodbred, S.L., Youngs, P.M., Ullah, Md.S., Pate, R.D., Khan, S.R., Kuehl, S.A., Singh, S.K., and Rahaman, W., 2013. Piecing together Holocene stratigraphy of the Ganges-Brahmaputra delta using Sr sediment geochemistry. 10th International Conference on Fluvial Sedimentology, University of Leeds, UK. July 14-19 (invited).

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Goodbred, SL., 2013. Diverse Landscapes of the Ganges-Brahmaputra delta: Implications for stability, resilience, and management. Joint Chapman/Penrose Conference on Coastal Processes and Environments under Sea-Level Rise and Changing Climate. Galveston, TX. April 14-19.

Overeem, I., K. Rogers, C. Thorne, Sarker, M., M. Steckler, S.Goodbred, C. Wilson, C. Small, M.van der Wegen, D. Roelvink, J.Atkinson, M. Zahid, N. Seeber, S. Nooner, J. Davis. 2014. Monitoring, Research and Analysis of the Bangladesh Coastal Zone, Worldbank Coastal Embankment Improvement Project Division, Dhaka, Bangladesh, March 2, 2014.

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R. Bhatta, P. Naren, K. Banerjee, R. Purvaja and A.K. Ray

The AUC team has focused on data assimilation.

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

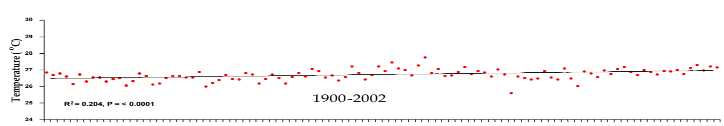
The SRTM data from the Gangetic delta have been collected and the digital elevation map (DEM) is prepared. The maps will be corrected at field with RTK GPS survey by validating the land elevation. Based on this topographic map the vulnerable areas along the delta will be classified. The DEM of the Gangetic delta region is shown in Figure 1.

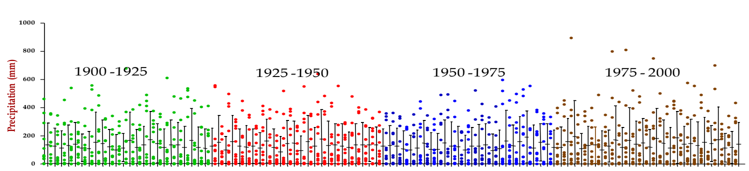
2. Collection of census data for economic, social, and demographic variables and association to geospatial data platforms for deltas

The village level census data on socio-economic and demographic variables for three decades, for the year from 1991, 2001, and 2011 has been collected and compiled from the coastal villages of deltaic region from upstream Farakka Barrage to downstream Hooghly estuary. The collected data is being incorporated in the Geospatial data platform.

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

Data on Gangetic delta hydrology, like river discharge, flooding and sediment transport has been collected from the literature survey. These data, including the bio-physical information in the Gangetic delta region, are being collected from secondary sources. Climatic variability on temperature and precipitation for 100 years from year 1900 to 2001 is being collected and analysed to understand the climate change effects in the Gangetic delta. Temporal variation of atmospheric temperature and precipitation over the Kolkata district of deltaic region is shown below.





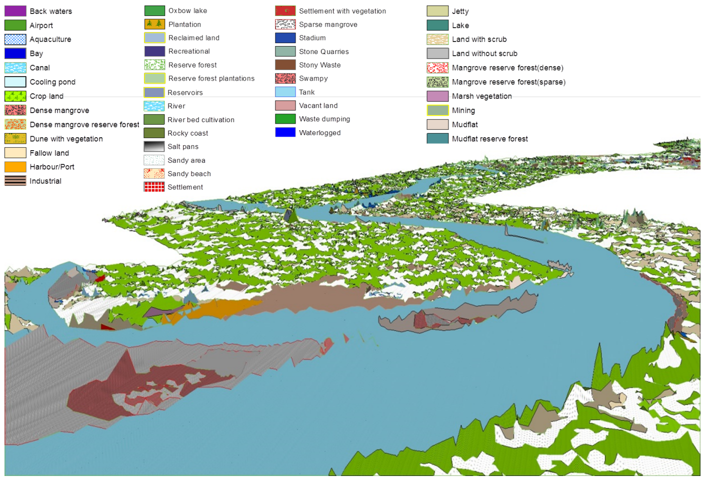


Figure 1. Three-Dimensional elevation view of the Ganges Delta

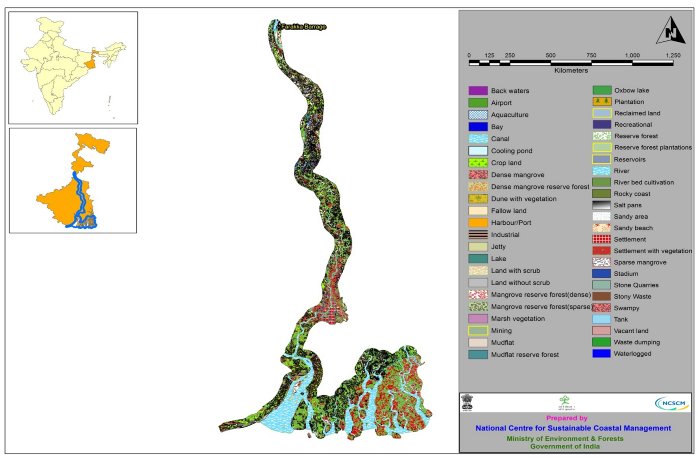


Figure 2. 2003: Land use and Land cover pattern of the Ganges Delta (Farakka Barrage to Bay of Bengal)

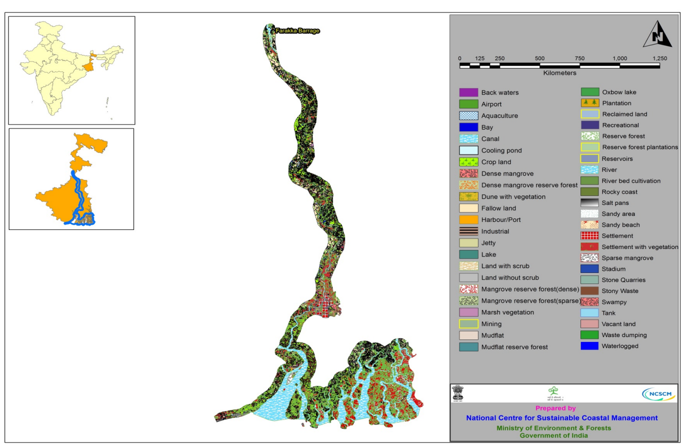


Figure 3. 2013: Land use and Land cover pattern of the Ganges Delta (Farakka Barrage to Bay of Bengal)

In addition to data assimilation, the AUC team have developed some mapping.

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

The time series multilayer satellite imagery are being processed for the land use/land cover (LU/LC) mapping of the Gangetic delta. The mangrove decline, land loss due to erosion, coastline change, urban development, etc shall be determined by analysing the time series LU/LC map of 30 years from 1990, 2003, and 2013.

The LU/LC of the Gangetic delta belonging to 11 districts with a study boundary of 5km on either side of Ganga river, upstream from Farakka Barrage to downstream Hooghly estuary are being mapped. Multi-temporal satellite data LANDSAT 5 TM with spatial resolution 30m for three consecutive years 1990, 2003, and 2013 are analysed for mapping. Geometric correction are carried out using well distributed control points based on SoI toposheets by utilizing ERDAS Imagine Software with RMS error of less than one pixel. Discrimination of various land use features have been delineated based on the visual key interpretation elements. False color composite spectral bands of Near Infrared, Green and Red bands are employed to carry out the LU/LC classification. Three spatial layers are vectorized using Arc GIS software. An image enhancement technique such as standard deviation is applied for more visualization of the image. The land use of the deltaic region for the Year 2003 and 2013 is already prepared (Figure 2 & 3) and for the year 1990 is under preparation.

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

In the coming year 2014 - 2015, the following tasks will be undertaken by AUC:
Finalisation of topographic features of Gangetic data with cartographic and land elevation survey using RTK GPS at the field level.

- The time series LU/LC map will be prepared and analysed for the land cover changes such as mangrove cover decline, land loss, land conversion from and to agricultural activities, etc., in the Gangetic delta.
- Demographic and socio-economic trends at a village level from deltaic region will be developed in GIS.
- Bio-physical, ecological, geomorphic, and climatic variability data will be collected from secondary sources (e.g. West Bengal State line departments)
- Based on the analysis of primary information and data it is inferred that the "downstream" farmers are made to incur additional cost in accessing water and other hydrological services, due to unsustainable farming practices by the "upstream" farmers.
- Payment-for-Ecosystem-Services (PES) model, based on the upstream farmers' willingness to accept a compensation package covering the opportunity cost of shifting to sustainable practices, is being developed.
- Prior to developing a PES model, a comprehensive survey assessing the effects of upstream farming practices on the downstream hydrological services will be undertaken.
- Finally it is proposed to assess the influence 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.

Further modeling and analysis has been conducted by VU and ACU teams.

5. Fast Track (FTP) Papers

The project team is working on a series of Fast-track papers. These are initially developed as internal white papers that are a statement of the condition of our knowledge; they can can highlight project priorities and identify optimum outputs. Hence the white papers can focus team effort on specific deliverables. However, as the Fast-track papers develop they can be refined, and project analyses and outputs can be integrated into them, so that they may be published as scientific publications that report the outputs of this project.

- **FTP1: Trends** -- An analysis of recent climatic, ecological, geomorphological, and economic trends in the Ganges-Brahmaputra-Mehgna, Mekong, and Amazon deltas (lead PI: John Dearing)

- **FTP2: Delta People** -- An analysis of the demographic and socio-economic characteristics of the Ganges-Brahmaputra-Mehgna, Mekong, and Amazon deltas (lead PI: Zoe Matthews)

- **FTP3: Modeling** -- An analysis of modeling approaches in deltas: hydro-eco-geomorphologic aspects and links to ecosystem services and human dimensions (lead PI: Irina Overeem)

- **FTP4: Vulnerability and Resilience** -- An assessment of vulnerability and resilience studies on deltas including metrics for socio-ecologic resilience (lead PI: Charles Vorosmarty/Zach Tessler)

- **FTP5: Data layers** -- An analysis of social and biophysical units in deltas: creating data coherency for modeling and assessment (lead PI: Eduardo Brondizio)

FT #	FT1	FT2	FT3	FT4	FT5
Theme	**Recent trends in the GB, Mekong, and Amazon deltas: climatic, ecological, geomorphological, and economic trends**	**Who are the delta people in the GB, M, and A deltas?: demographic and socio-economic trends**	**Modeling approaches in deltas: hydro-eco-geomorphologic aspects and links to ecosystem services and human dimension**	**Review of vulnerability and resilience studies on deltas including metrics for socio-ecologic resilience assessment**	**Social and biophysical units in deltas: creating data coherency for modeling and assessment**
Leader	John Dearing	Zoe Matthews	Irina Overeem	Charles Vorosmarty/Zach Tessler	Eduardo Brondizio
Co-leader			Attila Lazar (GB modeling)	Fabrice Renaud	Efi Foufoula-Georgiou (remote sensing, downscaling, aggregation and disaggregation, etc.)
Collaborators	Munsur Rahman (GB)	Zita Sebesvani (Mekong)	Claudia Kuenzer (ecosystem services Mekong)	Zita Sebesvari (delta resilience assessment, Mekong)	Zach Tessler
	Zita Sebesvani (Mekong)	Fabrice Renaud (Mekong)	Alice Newton (urban deltas and coastal management)	Efi Foufoula-Georgiou (theoretical approaches to resilience)	
	Fabrice Renaud (Mekong)	Sandra Costa (Amazon)	Hans Durr (modeling and comparison of three deltas)	Marcel Marchand (resilience metrics and delta resilient classification schemes)	
	Claudia Kuenzer (Mekong)	Ramesh Ramachandran (Demegraphic and occupational changes in Ganges delta)	Phillipe Van Cappellen (typology of nutrient filtering in deltas)	Edward Anthony (environmental issues on the Mekong and Amazon (downdrift muddy coasts sourced by the Amazon - the Amazon-Orinoco coast).	
	Tim Funkenberg (Mekong)		Katsuto Uehara (numerical modeling of nearshore to shelf-scale processes including those on deltaic coasts)	Alice Newton (delta resilience assessment, Mekong)	
	Yoshi Saito (Mekong)		Akiko Tanaka (change detection analysis in deltas)	Yoshi Saito (environmental problems and risks from viewpoints of morphodynamics, geology and sedimentology for deltas of Asia)	
	Toru Tamara (Mekong)		Ramesh Ramachandran (Nutrient conservation dynamics in Ganges delta using LOICZ and NANI model)	Claudia Kuenzer	
	Nguyen Van Lap (Mekong)				
	Edward Anthony (Amazon & Mekong)				
	Ramesh Ramachandran (Climatic variability and deltaic ecology in Ganges)				

5.1. FTP1: *Recent trends in the GBM, Mekong, and Amazon deltas: climatic, ecological, geomorphological, and social-economic. (Lead PI: John Dearing)*

Potential contributors: John Dearing/Zoe Matthews/Robert Nicholls/Sylvia Szabo (All deltas), Efi Foufoula-Georgiou (All deltas), Steven Goodbred Jr. (GBM), Munsur Rahman (GBM), Zita Sebesvani (Mekong), Fabrice Reneaud (Mekong), Claudia Kuenzer (Mekong), Tim Funkenberg (Mekong), Yoshi Saito (Mekong), Toru Tamara (Mekong), Nguyen Van Lap (Mekong), Tracy Farrell (Mekong), Edward Anthony (Mekong and Amazon), Scott Hendrick (Amazon), Eduardo Brondizio (Amazon), Caio De Auraujo Barbosa (Amazon)

The aim of FTP1 is to compile monitored, documented and reconstructed records/time-series in each delta covering the past 100-200 years maximum with emphasis on annual/monthly data for the last 50-60 years up to the present.

From analyzing these records singly and in combination we can create a macro-scale, evolutionary perspective that will enable us to explore the changes in social-ecological dynamics, including negative/positive trends, frequency-magnitude regimes, driver-responses, transient dynamics and critical transitions. In turn, these analyses will allow us to engage with the fundamental questions in WP1: (1) How do the dynamics of a delta, including its main processes, reservoirs, and feedback loops, steer the system toward a particular equilibrium state? (2) How are these dynamics are affected by human intervention and ongoing environmental change, especially with regard to maintaining a sustainable subaerial delta plain for human occupation? (3) What are the demographic and urban trajectories in delta regions with respect to population change, rates of poverty, and indicators of human well-being? (4) What types of governance arrangements may help to facilitate and/or limit solutions to intricate multi-scalar problems of management, protection, and mitigation in delta regions?

Defining the delta area

From a biophysical perspective, there seems to be some support to use the 'first distributary' as the first means to define the apex of each delta:

- for the Mekong this is at Phnom Penh (~8 m asl and ~250 km inland)
- for the Amazon this is the distributary just west of Gurupá (~25 m asl and ~330km inland);
- for the Ganges-Brahmaputra this is the Ganges/Hoogly junction (~17 m asl and ~425 km inland).

But for some of the objectives in the BF proposal this definition may not always be appropriate. For example, for the Ganges-Brahmaputra we often refer to the social-ecological system in coastal Bangladesh. For the Mekong, we suggest a large area definition because one aim is to assess the importance to local, national and international food security. For the Amazon, the proposal talks about the impact on Belem and Macapa but also the effects on coastal wetlands extending 1500 km northwards.

Data sets

For each delta, as define above, we would like to find records/time-series for the following major variables at specific sites within the delta or more generally for the delta region:

<u>Boundary conditions/macro drivers</u>

Regional climate (T, P, cyclones)
River water discharge

River suspended/bedload sediment discharge
River channel change
Coastal erosion
Subsidence rates
Sea level change
Groundwater levels
Dams/barrages

<u>Biophysical conditions</u>
Provisioning services
- Agricultural crop production
- Agricultural animal production
- Fisheries
- Forest products

Supporting/regulating services
- Surface water quality
- Groundwater quality
- Biodiversity/habitat
- Hazard protection (e.g deaths, crop damage, costs)
- Land production/losses

Cultural services
- Tourism
- Sacred sites

<u>Social-economic conditions</u>
Land use/cover
Urban settlement
Infrastructure (e.g. road/rail development/flood defences)
Human population/numbers
Human population/mortality/age structure
Education
Sanitation
Regional gross domestic product
Levels of poverty
Income/capita
Governance/policy

5.2. FTP2: *Who are the delta people in the GB, M, and A deltas?: demographic and socio-economic trends" (Lead PI: Zoe Matthews)*

An assessment of the changes in socio-demographic and occupational status along Ganges Delta, India

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Introduction:
Deltas are one of the most biologically-productive ecosystems in the world. The degradation of the delta region due to a variety of human activities within and outside the delta area has become a major environmental concern in India. Industrial, urban and agricultural effluent, intensive aquacultures are some of leading causes of this degradation. Understanding the human causes of degradation of delta and its impact would require a thorough knowledge of changes in the socio-demographic and institutions within and outside the delta region. Land, marine life, forests and crop land have alternative uses to different sets of user and modifications to such uses could have adverse impacts on delta productivity.
The main objectives of 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.

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 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.

1.0 Study Area (Ganges Delta Region in West Bengal)

The Ganges delta is one of the world's largest deltas where two-thirds of it is located in South Asian region of Bangladesh and the rest in the Indian state of West Bengal. The delta extends from the Hooghly River on the west to the Meghna River on the east. It forms the flood plain of three important rivers – Ganges, Brahmaputra and Meghna. The width of the delta is approximately 350 km across the Bay of Bengal coast and it has a surface area of over 100,000 km^2. The Ganges delta is a particularly fertile region supporting one of the most densely populated regions in the world.The scope of the analysis is limited to 9 selected districts of West Bengal that fall along the delta regions – Maldah, Murshidabad, Nadia, Bardhaman, Hooghly, 24 Parganas (N), 24 Parganas (S), Howrah and Kolkata. The study area is shown in Figure 1.

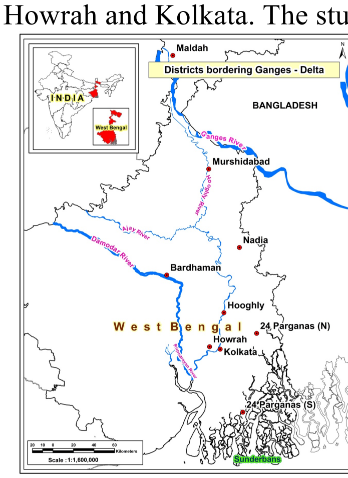

Figure 1. Districts Bordering Ganges Delta, India

1.1 Population and Sex Ratio

West Bengal is one of the most populated states in the country. Its population has increased by 35 % between 1991 and 2011 in spite of a decreasing trend in fertility rates in the state. The population density, defined as the number of persons per square kilometres, in the state has increased by 13 % to 1029 persons per square kilometre during the period. Maldah has reported highest growth in population density by 51 % between 1991 and 2011 while Kolkata has reported the least at 2 %. Urban populations at the districts have been increasing a faster rate than rural population owing to mass migration, greater employment opportunities and improved infrastructural facilities at urban centres.
Sex ratio defined as the number of females per 1000 males in the population, is an important social indicator to measure the extent social dependency of women on the resources. Changes in sex composition largely reflect the underlying socio-economic and cultural patterns of a society in different ways. The trends in the male-female population have shown an almost stagnant trend with little variation in the three reporting decades. In 2011, Kolkata posts one of the lowest sex ratios in the state while Hooghly, with 958, posts the highest ratio among the districts presently analysed. Although Kolkata posts one of the lowest sex ratios in the state, it records the highest growth in the ratio increasing by 13 % between 1991 and 2011.

Table 1. Population in Ganges Delta Region [1](* In Million)

	Population 1991			Population 2001			Population 2011		
District	**Total***	**Density**	**Sex Ratio**	**Total***	**Density**	**Sex Ratio**	**Total***	**Density**	**Sex Ratio**
Maldah	2.63	706	938	3.29	881	948	3.98	1068	939
Murshidabad	4.74	890	943	5.86	1101	952	7.10	1333	957
Nadia	3.85	981	936	4.60	1172	947	5.16	1315	947
Bardhaman	6.05	861	899	6.89	985	921	7.71	1102	943
Hooghly	4.35	1383	917	5.04	1601	947	5.51	1753	958
24 Parganas (N)	7.28	1779	907	8.93	2181	927	10.00	2444	949
24 Parganas (S)	5.71	574	929	6.90	694	938	8.16	820	949
Howrah	3.72	2542	881	4.27	2913	906	4.85	3306	935
Kolkata	4.39	23783	799	4.57	24760	828	4.49	24348	899
Total/Average	**42.7**	**3722**	**906**	**50.3**	**4032**	**924**	**57.1**	**4165**	**942**

1.2 Child Population

Child population consists of the proportion of the total population of the country which lies in the age group of 0-6 years which reflects the growing dependence of a delicate segment of the population. It is alarming to note that the 0-6 child sex ratio has consistently declined over the past 3 decades for all the districts in our analysis. Although Hooghly has one of the highest adult sex-ratios of the districts analysed, it has posted the largest decline in the child sex-ratio from positive 1378 females per 1000 males in 1991 to 952 females per 1000 males in 2011. This accounts for a 31 % drop in 0-6 child sex-ratio for Hooghly. The rest of the districts have posted only a marginal drop in ratios ranging from 2 % to 1 %.

[1]Registrar General and Census Commissioner, Census of India, Ministry of Home Affairs 2013

Table 2. Population (0-6 Years) and Sex Ratio in Ganges Delta[2]

District	Population 1991		Population 2001		Population 2011		population (%) 1991	population (%) 2001	population (%) 2011
	Total*	Sex Ratio	Total*	Sex Ratio	Total*	Sex Ratio			
Maldah	0.54	960	0.63	964	0.60	950	20.82	19.45	15.27
Murshidabad	0.99	977	1.04	972	1.01	968	20.95	17.8	14.27
Nadia	0.64	983	0.60	972	0.52	960	16.63	13.17	10.16
Bardhaman	0.98	959	0.90	956	0.83	951	16.22	13.1	10.78
Hooghly	0.64	1378	0.60	951	0.53	952	14.83	11.96	9.66
24 Parganas (N)	1.10	969	1.05	958	0.95	956	15.13	11.8	9.57
24 Parganas (S)	1.08	973	1.05	964	1.02	963	19	15.2	12.57
Howrah	0.55	962	0.51	956	0.52	962	15.01	12.01	10.78
Kolkata	0.42	955	0.39	927	0.33	933	9.57	8.53	7.55
Average	**6.9**	**1013**	**6.8**	**958**	**6.3**	**955**	**16.46**	**13.6**	**11.18**

* In Millions

Overall the share of the 0-6 age group population has declined by 5% during the last 20 years indicating the decline in the non-worker category of the total population.

1.3 Literacy

Education can be classified as an investment of great significance for social and economic development. It contributes to better health, higher productivities and income, and increased participation in community life. Literacy rate is an important indicator of development of a society. The Human Development Index uses literacy rates along with school enrolment rates as an index of education for any particular country. Table 3 presents the literacy rates in the districts of the delta region. Among the nine districts, 24 Parganas (North and South) records a high growth rate in the literacy levels.

Table 3. Literacy Rates in Ganges Delta Region (% of Total Population)[3]

District	1991			2001			2011		
	Total	Male	Female	Total	Male	Female	Total	Male	Female
Maldah	28.2	18.7	9.5	41	24.7	16.4	52.3	28.9	23.4
Murshidabad	30.3	19	11.3	45.4	26	19.4	57.1	30.6	26.4
Nadia	43.8	26	17.8	58	32.6	25.4	67.4	36.3	31
Bardhaman	51.9	31.6	20.3	62.2	36.3	25.9	68	37.8	30.2
Hooghly	56.9	33.8	23.1	66.8	37.7	29.1	73.9	40.1	33.8
24 Parganas (N)	56.7	33.4	23.3	69.5	38.9	30.6	76.1	40.5	35.5
24 Parganas (S)	44.6	28.9	15.7	59.8	35.2	24.6	67.8	37.3	30.5
Howrah	57.5	34.6	22.8	68.7	39	29.7	74.3	40	34.3
Kolkata	70.2	41.5	28.7	75	42.6	32.4	79.8	42.8	36.9
Average	**48.9**	**29.7**	**19.2**	**60.7**	**34.8**	**25.9**	**68.5**	**37.2**	**31.3**

[2] Registrar General and Census Commissioner, Census of India, Ministry of Home Affairs 2013
[3] Registrar General and Census Commissioner, Census of India, Ministry of Home Affairs 2013

The literacy rate in the state improved from 57.7 per cent in 1991 to 68.6 per cent in 2001 showing an increase of 10.9 %age points during 1991-2001. The literacy rate in India as a whole was 64.82 per cent which was lower than the West Bengal literacy rate. The overall literacy rate of the delta region has increased by 20 % indicating greater investments in the education sector by both public and private agencies and also higher levels of income and consumption. As of 2011, North 24 Parganas reported the highest literacy rate of 76.08 % among the districts analysed while Maldah reported the lowest rate of 52.3 %. Murshidabad posts the largest increase in literacy rates growing from 30.3 % in 1991 to 57.1 % in 2011. The districts with the highest female literacy rates include 24 Parganas North and Kolkata in 2011 indicating a positive correlation between economic growth and social development in highly urbanised centres.

1.4 Economic Livelihoods

The Census of India 2001 broadly classifies the population into workers and non-workers. The working population is further classified into main-workers and marginal workers. Table 4captures the changes in livelihoods patterns in the Ganges delta region between 2001 and 2011.
Table 4 shows that during the 10 year period (2001-2011) the proportion of workers has increased marginally by 2 %whereas the proportion of non-workers has increased significantly by 22 % in spite of the growth in literacy level, infrastructure and urban development. During the same time period, while the proportion of main workers has dropped by 4.5 %, the proportion of marginal workers has increased by 21 %. This indicates the inability of the economy in the delta region to absorb qualified and skilled manpower in its workforce.

Table 4. Working Population in the Ganges Delta Region[4]

Districts	2001					2011				
	Total Population *	% Non-Workers	Workers			Total Population *	% Non-Workers	Workers		
			Workers - % of Total Population	Main Workers (% of Workers)	Marginal Workers (% of Workers)			Workers - % of Total Population	Main Workers (% of Workers)	Marginal Workers (% of Workers)
Maldah	3.29	34.9	40.7	72.1	27.9	3.98	61.4	38.6	68.3	31.7
Murshidabad	5.86	40.8	34.2	83.4	16.6	7.10	63.5	36.5	78.1	21.9
Nadia	4.60	41.8	35.1	87.0	13.0	5.16	64.3	35.7	86.6	13.4
Bardhaman	6.89	40.3	35.5	77.6	22.4	7.71	62.3	37.7	74.4	25.6
Hooghly	5.04	40.8	36.9	82.2	17.8	5.51	61.0	39.0	79.6	20.4
24 ParganasN	8.93	42.6	33.4	87.8	12.2	10.00	64.3	35.7	85.6	14.4
24 Parganas S	6.90	42.7	32.5	74.8	25.2	8.16	63.7	36.3	67.6	32.4
Howrah	4.27	43.2	33.7	85.1	14.9	4.85	62.5	37.5	82.2	17.8
Kolkata	4.57	39.5	37.6	94.5	5.5	4.49	60.1	39.9	87.8	12.2
Average	**50.3**	**40.7**	**35.5**	**82.7**	**17.3**	**57.1**	**62.6**	**37.4**	**78.9**	**21.1**

* In Million

1.5 Fish Production

Figure 1 provides the species wise catch in the Hugli-Matla estuary during 2006-07 to 2010-11which is based in the species wise fish landing is available with the Directorate of fisheries,

[4]Registrar General and Census Commissioner, Census of India, Ministry of Home Affairs 2013

Government of West Bengal. The overall decline in fish catch over the years has had a significant impact on the income levels of workers engaged in estuarine fishing. Catches of fish species such as Mullets and (Panaeid and Non-Panaeid) Prawns have declined by more than 70 % between 2006 and 2010 and seem to be on a decreasing trend. The production of Hilsa, one of the most important river fish, has declined by almost 30 % during the same time period but has shown marginal improvement (9 %) in 2011 when compared to 2010 estimates.

1.6 Agriculture

The overall economic growth of the state has been driven by the growth in the agricultural sector particularly due to increased production of food-grains and pulses. The rapid growth in West Bengal's agricultural production beginning in the early 1980s can be attributed to the adoption of high-yielding variety of seeds and chemical based farming practices. Table 5 highlights the total area under each type of crop production for all the selected districts along the Ganges delta and the yield provided is the average yield rates across the nine districts.

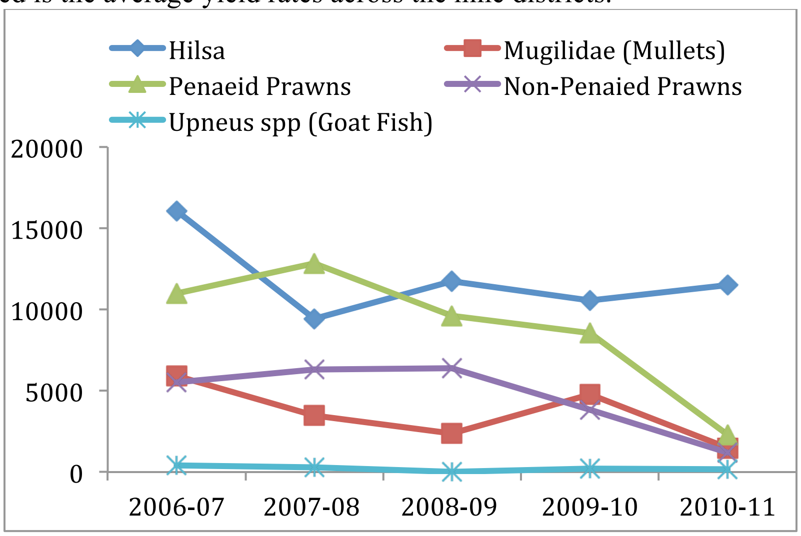

Figure 2. Fish Landing by Species in the Ganges Delta Region[5]

Food-grains and oilseeds have shown the highest increase in yield rates over the years and have grown by over 75 % and 100 % respectively between 1980 and 2008. The area under the production of pulses has shown a decline but has still managed to improve yield levels over the years. The decline in area and increase in yield with the help of fertilizer based farming practices could have adverse impacts on the pollution load in the delta region.

Table 5. Yield and Area under Different Crops in the Ganges Delta Region[6]

Year	Pulses		Food Grains		Oilseeds	
	Area	Yield	Area	Yield	Area	Yield
1980-81	307	524.87	2131.4	1446.37	166.3	525.75
1990-91	221.8	528.25	3006.5	1938.62	285.6	912.75
2000-01	181.3	858.25	2731.7	2301.25	364.8	928.37

[5]Mukerjee,M; Chakraborty, C. (2013) Fish catch in river ganga and its tributaries in West Bengal and issues of livelihood of small fisher, International Conference on Small Scale Fisheries Governance: Development for Wellbeing and Sustainability, Hyderabad

[6]Sau, S. (2010), Database for planning and development in West Bengal, Volume 1: Districts of West Bengal, Kolkata

2007-08	139.1	745.25	2899.3	2573.25	397.2	1055
% Change (1980-2008)	-54.7	42.0	36.0	77.9	138.8	100.7

1.7 Growth in Gross Domestic Product (GDP) and Per Capita GDP

In 2011, Kolkata, being one of the metropolitan cities in India, has the highest per capita income in the state with the latest estimate of Rs. 77,705 closely followed by Bardhaman. The district with highest growth in per capita income was recorded by 24 ParganasNorth increasing from Rs.13,834 in 2001 to Rs.48,341 in 2010-11. Maldah, on the other hand, has recorded the lowest growth in per capita with an annual growth of 11.2 % between 2001 and 2011.Overallthe per capita GDP in the delta region has increased by over 150 % in 10 years while the GDP alone has increased by 106 %.

Table 6. Total GDP (in billion INR) and Per Capita GDP (in INR) in Ganges Delta Region[7]

District	2000-01		2004-05		2010-11	
	Total GDP*	Per Capita GDP	Total GDP*	Per Capita GDP	Total GDP*(E)	Per Capita GDP
Maldah	59.2	16,899	71.62	18,775	101.5	35,763
Murshidabad	93.3	14,906	123.3	18,153	178.0	36,726
Nadia	88.3	17,932	106.2	20,158	154.2	41,084
Bardhaman	157.7	20,071	223.5	27,310	318.0	52,748
Hooghly	103.9	18,636	136.1	23,264	215.3	49,856
24 Parganas (N)	138.1	13,834	244.1	23,008	413.5	48,341
24 Parganas (S)	116.5	14,974	168.8	20,568	251.0	40,655
Howrah	87.2	18,242	116.1	23,313	183.3	48,749
Kolkata	180.4	35,404	197.2	38,393	300.1	77,704
Average	**113.8**	**18,988**	**154.1**	**23,660**	**234.9**	**47,959**

E: Estimate; * In 2005 Prices

Growth in income and employment is essential for understanding the progress of development. Although the employment was showing a negative sign with an increase in the share of non-worker category the GDP and Per Capita GDP is showing substantial increase in the period. The average per capita GDP in the delta region has more than doubled during the 10 year period although the rate of population growth has increased by 2 % annually.

1.8 Sector Contribution to Net Domestic Product (NDP)

Table 7 indicates the %age contribution of each sector in particular district to the district net domestic product (NDP). As per 2010 data Kolkata's agriculture and allied activities contribute the least to the district NDP with 0.2% while Murshidabad contributes the highest with 37.5 %. Bardhaman's industrial sector contributes the highest to district NDP with 17% while Nadia and Kolkata's industrial sector are among the lowest contributing sector. In the services sector,

[7] Government of West Bengal, 2013 State domestic product and district domestic product of West Bengal 2012 (2013) Department of Statistics and Programme Implementation, Bureau of Applied Economics and Statistics, Kolkata

Kolkata, Howrah and 24 Parganas (N & S) are among the highest contributors to the district NDP. During the 10 year period between 2001 and 2010 data all districts in Ganges delta region recorded a fall in agricultural output with Bardhaman recording the largest decline by over 40 %. The %age workforce employed in the agricultural sector of the delta region has remained constant over the 10 year period but the contribution of sector's output in the NDP has marginally declined from 26.7 % in 2001 to 22.4 % in 2010. Industrial output for all districts in the region recorded a decline in output except Maldah that posted a 6 % increase in industrial output. Overall, the contribution of the industrial sector to the district NDP and the %age workforce employed have remained constant over the 10 year period. In the services sector all districts have recorded a positive improvement.

Table 7. Estimates of Net District Domestic Product (in %) by Industry of Origin in Ganges Delta Region[8][9]

District	**2001**						**2010**					
	Agriculture		Industry		Services		Agriculture		Industry		Services	
	% Workforce	% NDP	% Workforce	% NDP	% Workforce	% NDP	% Workforce	% NDP	% Workforce	% NDP	% Workforce	% NDP
Maldah	51.5	40	15.6	8.9	32.8	51.1	52.1	34.1	12.8	9.5	35.1	56.5
Murshidabad	46.7	38.8	20.4	9.9	32.9	51.3	47.2	37.5	18	9.1	34.8	53.4
Nadia	43	39.7	11.4	7.7	45.5	52.6	47	36.1	9.2	6.8	43.9	57.1
Bardhaman	44.7	35.7	4.9	8.5	50.4	55.7	45.2	20.6	4.3	17	50.5	62.4
Hooghly	39.2	26.8	5.2	12	55.6	61.2	39.2	23.7	5.2	10.1	55.6	66.2
24 Parganas (N)	23.7	18.6	4.4	11.5	71.9	69.9	24.9	15.4	4.4	9.9	70.8	74.7
24Parganas (S)	42.1	27.2	6.1	14	51.7	58.8	39.2	22.3	8.1	10.1	52.7	67.6
Howrah	15.4	12.5	11.5	18.1	73.1	69.4	14.4	11.6	16.4	15.4	69.2	73
Kolkata	0.7	0.9	3.1	4.1	96.3	95	1.6	0.2	3.8	3.5	94.6	96.3
Average	**34.1**	**26.7**	**9.2**	**10.5**	**56.7**	**62.8**	**34.5**	**22.4**	**9.1**	**10.2**	**56.4**	**67.4**

1.9 Road Infrastructure

Roadways serve as a crucial infrastructural component to accelerate economic growth and development. As of 2001, West Bengal accounted for 3.5 % of surfaced road length and 3.7 % of total road length of the whole country. Table 8 provides information on the length of the roadways maintained by the different governmental agencies operating within the districts in the Ganges delta region.

Table 8. Roadways maintained by Public Works Department, Municipalities and Corporations (in km)

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[8] Sau, S. (2010), Database for planning and development in West Bengal, Volume 1: Districts of West Bengal, Kolkata

[9] Government of West Bengal , 2012: State domestic product and district domestic product of West Bengal 2011, Department of Statistics and Programme Implementation, Bureau of Applied Economics and Statistics, Kolkata

District	Maintained by PWD		Maintained by Municipality & Corporation	
	2001	2011	2001	2011
Maldah	609	727	-	-
Murshidabad	1184	1252	-	-
Nadia	973	1026	-	-
Bardhaman	1966	1974	-	-
Hooghly	1137	1210	-	-
24-Parganas N		1391	-	-
24-Parganas S		1262	-	-
Kolkata	20	20	1830	1909
Howrah	540	553	176	310

	2001		2011	
Districts	Total Households*	% Household with sanitation	Total Households*	% Household with sanitation
Bardhaman	1.38	41.6	1.7	55.7
Howrah	0.83	60.9	1.02	74.7
Hooghly	1.02	55.3	1.26	71.2
Kolkata	0.91	95.7	0.96	94.9
Maldah	0.62	21.3	0.83	31.7
Murshidabad	1.12	23.1	1.56	39.5
Nadia	0.94	53.7	1.23	77.6
24 Parganas (N)	1.79	75.3	2.28	87.5
24 Parganas (S)	1.31	41.8	1.77	62.6
Average	9.92	52.1	12.61	66.2

1.10 Water Access

Access to water is one of the most fundamental infrastructural facilities that need to be ensured by the state. Table 9 brings out the domestic sources of water. There are four main sources of water that are currently available – tap, tube well, well, and hand pump. Kolkata, being the only urban centre, has the highest rate of access to water among the districts analysed with 89.7 %. The lowest rate of water access is recorded by Murshidabad with only 72 % of the household having access to water but is also the district with the most hand pumps installed. Overall, the hand pump appears to be the most used source of acquiring water at homes closely followed by the tap.

Table 9. Sources of Water Access 2011 in Ganges Delta Region[10]

Districts	Total Households*	Hand pump (%)	Tap (%)	Tube well (%)	Well (%)	All others (%)
Bardhaman	1.7	47.6	30.7	10.6	10.3	0.8
Howrah	1.02	48.8	33.2	14.6	2.6	0.8
Hooghly	1.26	59.9	30.4	8.2	0.9	0.6
Kolkata	0.96	6.4	77.0	15.2	0.8	0.6
Maldah	0.83	68.3	8.3	9.6	13.2	0.6
Murshidabad	1.56	83.6	4.7	10.0	1.1	0.6
Nadia	1.23	82.4	7.8	8.2	0.7	0.8
24 Parganas (N)	2.28	47.1	37.8	13.5	0.7	1.0
24 Parganas (S)	1.77	72.1	10.2	16.8	0.2	0.7
Average	12.61	57.4	26.7	11.9	3.4	0.7

**in million*

[10] Registrar General and Census Commissioner, Census of India, Ministry of Home Affairs 2013

Conclusion:

Over the last two decades the total population in the region bordering Ganges delta in West Bengal has increased by over 140 million indicating the increasing human pressure on the resources. The density of the population is also showing significant increase during the last two decades with increased urban growth and dependency on the ecological goods and services. The sectoral share of the NDP from agriculture remained around 22 % ranging from 36 % in Maldah to 0.2 % in Kolkata during the last 5 years which is significantly higher than 14 % at the national level. The bias against the female is represented by a decline in female population. The decline in the sex ratio is also reflected in the age group 0-6years which indicates the future adverse scenarios of increasing social problems. The increase in literacy level has not resulted in decline in the proportion of non-workers and agricultural labourers during the period indicating a high dependence of the local communities on the existing working population and on agriculture which could also lead to higher pressure on resources.

The analysis of the professional classification of workers, during the last decade, shows the shift in status from owner cultivator to agricultural labourer category. This shift could be mere consolidation of small and marginal farms by larger land-owner/farmers. The small and marginal farming may have become uneconomical and many of them have been forced to sell their land but still continue to work as agricultural labourers. The fish catch in the delta area, as one of the indicators of productivity and health of the ecosystem shows the impact of pollution/increased effort and other anthropogenic factors. Most estuarine fish are showing a declining trend during the last five years.

Access to infrastructural services such as water indicates that the entire region lacks access to clean and assured drinking water supply as the majority of the households are dependent on hand pumps for access to water. Only 26 % of the population have access to tap water. The study, however, needs further examination of the land-use/land cover changes and also sources of pollution in the region which could impact the productivity of the delta.

References:

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5.3. FTP3: *Modeling approaches in deltas: hydro-eco-geomorphologic aspects and links to ecosystem services and human dimension (Lead PI: Irina Overeem)*

Co-leader: Attila Lazar (GB modeling)
Contributors: Claudia Kuenzer (ecosystem services Mekong), Alice Newton (urban deltas and coastal management), Hans Durr (modeling and comparison of 3 deltas), Phillipe Van Cappellen (typology of nutrient filtering in deltas), Katsuto Uehara (numerical modeling of nearshore to shelf-scale processes including those on deltaic coasts), Akiko Tanaka (change detection analysis in deltas)

Nutrient conservation dynamics in Ganges Delta using LOICZ and NANI Biogeochemical Approach

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1.0 Budgeting of Nutrients (C-N-P) using LOICZ Biogeochemical Model

Anthropogenic inputs of all forms of carbon (C), nitrogen (N) and phosphorus (P) from rivers have increased during the thirty years period between 1970 and 2000 at a global scale [*Smith et al.*, 2003; *Seitzinger et al.*, 2010]. These enhanced inputs of C, N, and P and the form of (dissolved inorganic, organic, particulate) nutrient inputs to coastal ecosystems contribute to numerous negative human health and environmental impacts, such as general loss of habitat and biodiversity, increased frequency and severity of blooms of certain species of harmful algae, eutrophication, hypoxia and fish kills [*Billen and Garnier,* 2007; *Diaz and Rosenberg*, 2008; *Seitzinger et al.,* 2010].

To quantify the impact of these nutrients on the estuaries, a number of models have been proposed to calculate the net budgets of C, N, and P in the estuaries, which apply simple mass-balance calculations to available data [*Swaney et al.*, 2012]. One such model is that of the Land Ocean Interaction in the Coastal Zone (LOICZ) that determines the capacity of estuaries to transform and store dissolved C, N and P [*Xu et al*., 2013]. This biogeochemical budgeting model has been implicated for the Ganges (Hooghly) estuary.

1.1 Hydraulics of Ganges Estuary

The Ganges (Hooghly) Estuary is one of the world's major estuaries, fed by one of the world's largest rivers, the Ganges (0.9 x 10^6 km^2) with a flow of 15,646 m^3 s^{-1} (1.6% of the world's combined river flow). It is a part of the world's largest delta (Ganges-Brahmaputra delta), which is a densely populated low-lying fertile plain. The Ganges-Brahmaputra riverine system supplies 262 million tons of sediments per year to the Bay of Bengal [*Stephanie*, 2007]. The Ganges estuary is situated between $21^{\circ}31'$ and $23^{\circ}20'$ N and $87^{\circ}45'$ and $88^{\circ}45'$ E and covers around 1380 km^2 of the state of West Bengal, India. The estuary meets the Bay of Bengal near Sagar Island. The semidiurnal tidal amplitude ranges from 4.42 m (Spring Tide) to 2.33 m (Neap Tide) [*Sadhuram et al.*, 2005]. The Hooghly estuary is a positive estuary, mixohaline in nature, turbid and funnel shaped. The estuarine reach of about 55 km length was divided into 3 topographical zones- 1) Upper or freshwater zone, 2) Estuarine or gradient zone and 3) Coastal waters. To accomplish the objectives of the present study, three compartments are considered (Box 1- River, Box 2- System and Box 3- Ocean) based on the salinity gradients of the estuary. The study area map delineating the three boxes is shown in (Figure 1).

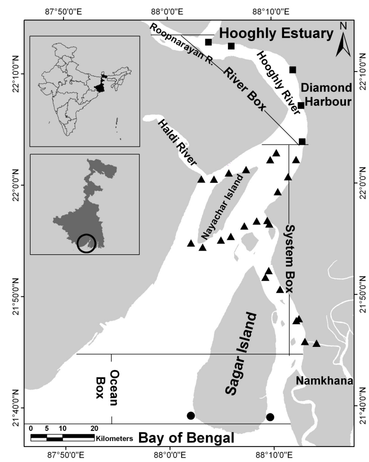


Figure 1. Location of Hooghly Estuary and sampling locations on the map of India

1.2 Material Budgets

i. Water and Salt Budget

The detailed water and salt budget and its seasonal variation in the estuary are given in (Table 1). The predicted water exchange time (λ) of the estuary was ~48 days during the dry and ~19 days during the wet season. Considering the total inflows and outflows, the water budget of the estuary displayed a seasonal dominance of fresh water during the wet, and sea water in the dry seasons. Lower residual flux in the dry season was related to higher water residence time. Long water-residence times play a key role in nutrient metabolism, as they allow the retention of anthropogenic phosphorus and nitrogen loadings in the sediment [*Souza et al.*, 2003; *Padedda et al.*, 2010]. Salt budget showed an overall positive salt balance in both the seasons in estuary.

Table 1. The water and salt budget of Ganges estuary during wet and dry season

Sampling seasons	Total fresh water input (10^6 m^3 d^{-1})			Residual flow (-) (10^6 m^3 d^{-1})	Mixing flux (10^6 m^3 d^{-1})	Estuary volume (10^6 m^3)	Residence time (λ) in days	Salt flux (10^6 m^3 d^{-1})
	River	Precipitation	Evaporation (-)					
Wet	259	18.4	1.7	276	166	8205	19	3341
Dry	86	3.8	4.2	86	85	8205	48	1526

ii. C-N-P budget

The seasonal and spatial fluxes of C, N and P of the Ganges estuary are given in Table 2. The net DIC flux was positive (96906 x10^3 mol d^{-1}) during wet season and negative (-6762 x10^3 mol d-1) during the dry season. The DIC budget model suggested that the estuarine region may be generating excess DIC during wet season, which can be substantiated due to the re-mineralization of riverine and/or in-situ production of organic carbon either in the form of DOC or POC. Whereas, during dry season the riverine DIC source becomes the estuarine sink. The Net flux of

DOC for both the seasons was negative (-8935×10^3 mol d^{-1} during wet season and -4794×10^3 mol d^{-1} during dry season). The presence of Sundarbans mangrove adjacent to estuary is providing lateral DOC input to the estuarine system from mangrove litter decomposition.

This study showed that the seasonal variations in the riverine DIN fluxes were large and so also the residual flux owing to large variation in the seasonal river inflow, though the concentration of DIN in the estuary remained almost at similar level. Both the seasons showed negative non-conservative fluxes of DIN (ΔDIN) but the rates varied remarkably on a seasonal scale. Unlike DIN, the wet and dry seasons showed positive net ΔDIP, indicating a net flux of DIP to the coastal sea from the estuary (Table 2).

Table 2. Summary of C-N-P fluxes of the Ganges estuary from LOICZ model

(x 10^3 mol d^{-1})	**DIC**		**DOC**		**DIN**		**DIP**	
	Wet	***Dry***	***Wet***	***Dry***	***Wet***	***Dry***	***Wet***	***Dry***
River Flux	425186	200023	67185	29315	8545	2497	485	75
Residual Flux	490824	166253	73803	24991	7035	1926	466	57
Mixing Flux	-31269	-27009	-8935	-4794	-967	-393	-27	-21
Net Flux	96906	-6762	15552	470	-542	-179	8	3
Residence Time	*33*	*120*	*37*	*127*	*38*	*129*	*32*	*177*

1.3 Nitrification and Denitrification

The N*fix*-D*enit* rate in the Ganges estuary is negative during both the seasons and varied from -0.48 mmol m^{-2} d^{-1} during wet season to -0.17 mmol m^{-2} d^{-1} during the dry season. In wet season, the ΔDIN values indicate higher degree of N sink which could be due to the transformation of DIN to PON as the estuarine region contained higher suspended particulate matter, which possibly adsorb the nitrogen in it. Another potential mechanism of DIN lost from estuary could be the de-nitrification process, which ultimately releases the gaseous phase of N_2 and N_2O to the atmosphere (Smith and Hollibaugh, 2006). This is seen from the LOICZ model where the negative denitrification rate (-0.48 mmol C m^{-2} d^{-1}) is noticed during the wet season (Table 3). The wet season was characterized by higher riverine DIN load (VqDINq) which suggested that at high N loads, the estuary could not fix DIN, instead lose N. This response has also been observed in other estuarine systems [*Giordani et al.,* 2008; *Padedda et al*., 2010] and possible a general phenomenon.

1.4 Net Ecosystem Metabolism (NEM)

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) (Table 3). Generally, the high residence time of DIP in the system could assist in the regeneration of DIP from organic matter [*Mukhopadhyay et al.*, 2006]. In addition, the natural effect of the phosphate buffer mechanism could cause the release of DIP to the water column from estuarine sediments [*Froelich*, 1988; *Sylaios*, 2003] and made the system a source of DIP. According to *Hung and Kuo* [2002], a system with positive ΔDIP, acts as a net producer of CO_2 ($p<r$), which is evident with reported high pCO_2 levels [*Mukhopadhyay et al*., 2006] in the Ganges estuary during both the seasons.

1.5 Nutrient Conservation in the Ganges

The nutrient budget through LOICZ biogeochemical model shows that, the Ganges estuary acts as a main conduit of land-derived nutrients of riverine influx to the coastal ocean. The estuary acts as a source for all nutrients in both seasons except for DIN where it acts as a sink. Even though nutrient concentrations are high and their longer residence times in the estuary is sufficient to trigger the primary production, high levels of SPM (> 100 mg l^{-1}) inhibits the light availability for photosynthesis and in turn their growth, makes the system net heterotrophic in both the seasons.

Table 3. Net Ecosystem Metabolism (NEM) and N*fix*-D*enit* in the Ganges estuary during wet and dry season

Sampling seasons	**NEM (p-r) (mmol m^{-2} d^{-1})**	**N*fix* - D*enit* (mmol m^{-2} d^{-1})**
Wet	-0.58	-0.48
Dry	-0.25	-0.17

2.0 Net Anthropogenic Nitrogen inputs from Ganges Basin

Nutrient input from land to the coastal systems is mainly carried from the terrestrial catchment of rivers [*Mackenzie et al.,* 2004]. This input varies with population density and its expansion (Smith et al 2005). Worldwide transport of nutrients from rivers to the coasts showed a two fold increase for both N and, P whereas decrease for Si [*Meyback,* 1998]. Nutrients and its export fluxes to the coastal systems are profoundly altered by various human activities such as agriculture, deforestation, urban development, fossil fuel burning and waste discharges [*Meybeck,* 1993; *Cole and Caraco,* 2001; *Smith et al.,* 2005). The Ganges river basin is one of the biggest in the world with total drainage area of 1.08 million km^2, and ~78% lies in the Indian subcontinent. It represents the most fertile agriculture belt, and witnessed high population growth, with exceptional growth of urbanization and industrialization [*Pandey,* 2013]. The Ganges brings massive input of nutrients to Bay of Bengal along its 2,525 km course from Himalaya. Varying nutrient loads and the shifting environmental conditions arise problems in the coastal water quality like harmful algal blooms, eutrophication, hypoxia and loss of biodiversity at local, regional and global scale [*Howarth et al.*, 2012]. As global change hazards accelerate, regular updates about the nutrient budgets in the coastal zone are needed for understanding the scale of human disturbances and the potential effectiveness of restorative actions for individual ecosystems [*Cloern,* 2001].

Nutrient accounting in the stressful environment of Ganges basin is an important tool to understand the dominant contributors in this region. NANI (Net Anthropogenic Nitrogen Inputs) is a budget model, which provides a good estimate of the nitrogen inputs associated with human activities to a watershed *Howarth et al.* [1996]. NANI is calculated as the sum of four major components: oxidized N deposition, fertilizer N application, agricultural N fixation, and N in net food and feed imports. Schematic diagram of the flow of nitrogen in NANI and its components were shown in Figure 2. Quality of the input data and the quantitative judgments are the most important aspect in any budget estimation. This initial attempt of NANI estimation for Ganges basin in India, made use of databases compiled at the global scale and some locally available information.

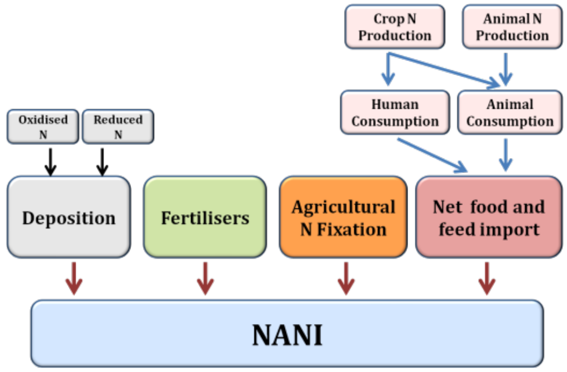
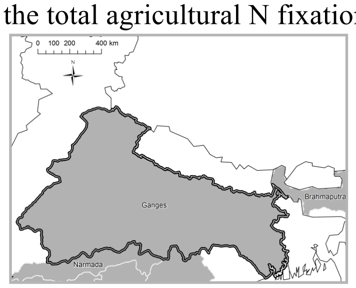


Figure 2. Flow chart of nitrogen in Net Anthropogenic Nitrogen Input (NANI)

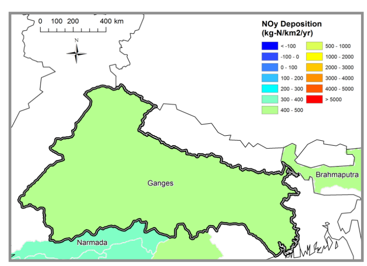
2.1 Conduits of N inputs from anthropogenic influences

Fertilizer N consumption rate was estimated to be about 4961 kg-N km^{-2} yr^{-1}, from district-level fertilizer consumption falling within the Ganges basin for the year 2000 [*Chanda et al.*, 2001]. Wide variation in the fertilizer consumption was found among the districts in the Ganges basin (Figure 3c). This region has seen exceptional growth in the agricultural sectors in the recent decades, with increase in the usage of nitrogenous fertilizers. Average fertilizer consumption in the districts was increased from 1.7 thousand tonnes in 1962-65 to a level of 102.6 thousand tonnes during 2003-06 [*Vinod Tare et al*., 2011].

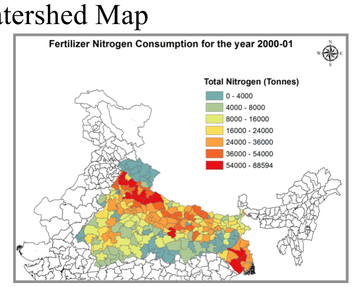
Limited available estimates of N species in depositional flux make it almost hard to accurately quantify the depositional fluxes. Although atmospheric nitrogen deposition is estimated using data from *Lamarque et al.* [2010], which includes oxidized N species only, and found to be 496 kg-N km^{-2} yr^{-1}. Regarding agricultural crops in the Ganges basin; Rice, wheat, sugarcane, lentils, oilseeds and potatoes are the chief crops, apart from the legumes and jute. The latter mainly present near swamps and lakes along the banks of the river. Multiple cropping is practiced in the major part of the basin, as it is heavily irrigated more than once a year. Total agricultural N fixation estimated from significant N fixing crops like soybean, groundnut, and peas as well as by adding pasture N fixation was found to be 441 kg-N km^{-2} yr^{-1}. Soybean crops contribute nearly 50% of the total agricultural N fixation.



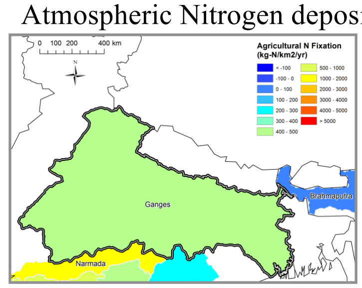
a) Watershed Map



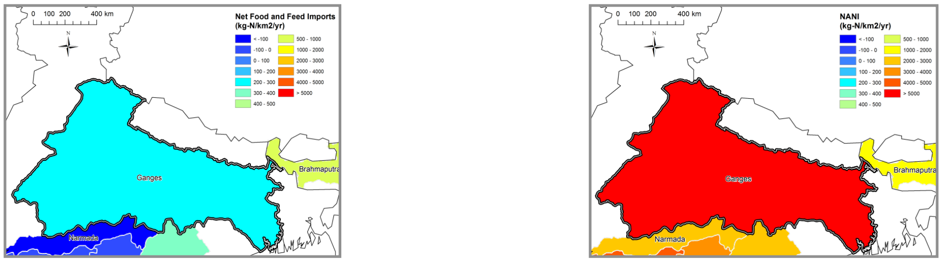
b) Atmospheric Nitrogen deposition



c) District-wise fertilizer nitrogen consumption



d) Agricultural Nitrogen Fixation



e) Net Food and Feed Imports f) NANI

Figure 3. Ganges basin; NANI and its components

Net food and feed imports are estimated as the difference between N in agricultural production (crops and livestock), which remove N from watersheds and into crop and livestock products, and consumption by humans and livestock, which ultimately adds to watershed N loads through manure and human waste. The Ganges basin has an estimated population of 125 million, which constitutes 1949 cities and towns, and average population density in the Ganges basin is 520 persons/km^2 as compared to 312 for India (Census 2001). From the population density (Census 2001) and human nitrogen intake rate [*National sample survey*, 2012], total human nitrogen consumption was calculated as 1792 kg-N km^{-2} yr^{-1} whereas livestock nitrogen consumption was 2325 kg-N km^{-2} yr^{-1}, as calculated from the livestock density [*Clements et al.*, 2002] and livestock nitrogen intake rate [*Dikshit and Birthal*, 2010]. Among the livestock consumption it was found that cattle, buffalo and goat contributes 54, 37 and 6% respectively; and the remaining from the sheep, pig and poultry. Livestock production from the Ganges basin accounts to 242 kg-N km^{-2} yr^{-1}, with major contribution (~76%) from the milk of cattle and buffalo. Nitrogen content in edible portion and percent edible portion of livestock products are estimated from Han et al. 2009. N associated with crop and pasture production in Ganges basin estimates to 3675 kg-N km^{-2} yr^{-1} with major contribution from sugarcane, wheat and rice. The net food and feed imports of Ganges basin were positive (200 kg-N km^{-2} yr^{-1}), indicating an excess of consumption over production. Fertilizer contributes major portion of N inputs to the net nitrogen input from the Ganges basin (Figure 4).

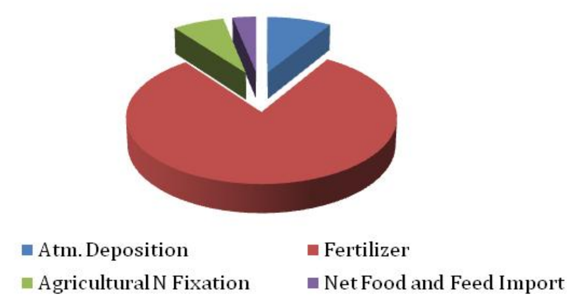


Figure 4. Proportion of NANI components in Ganges Basin

Overall Ganges showed high NANI value (Figure 3f), driven mainly by high agricultural fertilizer inputs which in turn dominates 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.

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5.4. FTP4: *Review of vulnerability and resilience studies on deltas including metrics for socio-ecologic resilience assessment (Lead PI: Charles Vorosmarty/Zach Tessler)*

Co-leader: Fabrice Renaud
Contributors: Zita Sebesvari (delta resilience assessment, Mekong), Efi Foufoula-Georgiou (theoretical approaches to resilience), Marcel Marchand (resilience metrics and delta resilient classification schemes), Edward Anthony (environmental issues on the Mekong and Amazon (downdrift muddy coasts sourced by the Amazon - the Amazon-Orinoco coast), Alice Newton (delta resilience assessment, Mekong), Yoshi Saito (environmental problems and risks from viewpoints of morphodynamics, geology and sedimentology for deltas of Asia), Claudia Kuenzer.

As reported above, several studies have been completed during the first year related to vulnerability assessment of deltas, ranging from topological analysis to environmental flux dynamics and indices of vulnerability defined and compared. These studies are currently compiled and compared towards an integrated presentation in the FTP4. Also, more integration of environmental with socio-economic factors as defining the vulnerability of a delta system must be advanced in the second year.

5.5. FTP5: *Social and biophysical units in deltas: creating data coherency for modeling and assessment (Lead PI: Eduardo Brondizio)*

Contributors: Efi Foufoula-Georgiou (remote sensing, downscaling, aggregation and disaggregation, etc.), Zach Tessler.

As different data sets continue to be collected in the first year of the project, the team is working towards establishing feasible frameworks for data coherency in terms of space-time scales (units) that can facilitate joint analysis of climate, environmental and socio-ecological variables.

6. Other Accomplishments

ICSU Sustainable Deltas 2015 (SD2015) Initiative

The Deltas team spearheaded a global initiative called "Sustainable Deltas 2015" (SD2015) which has been endorsed by ICSU (International Council of Scientific Unions). The SD2015 is a statement of urgency for global cooperation and a call to arms to the global community of citizens, scientists, policy makers, and funders to work together towards accelerating the understanding and sustainable solutions of these critical systems. The specific 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 initiative committed to understanding these complex socio-ecological systems as the cornerstone of ensuring preparedness in protecting and restoring them in a rapidly changing environment. Activities to launch SD2015 are in progress and events will take place in many parts of the world during 2014 and 2015.

Affiliation with the Land-Ocean Interactions in the Coastal Zone (LOICZ) program

The deltas project has now been formally accepted as an affiliated project with LOICZ http://www.loicz.org/projects/documents/051827/index_0051827.html.en

This allows us to link with other LOICZ projects.

Affiliation with Linked Institutions for Future Earth (LIFE)

The BF-DELTAS project is in synergy with another international project that the lead PI is leading, namely a project funded by the NSF called LIFE (Linked Institutions for Future Earth). The overarching goal of LIFE is to create an international network of researchers, institutions, and experimental sites/field observations dedicated to advancing the quantitative predictive understanding of the Earth surface system. LIFE centers on action-oriented interdisciplinary research as well as creating the next generation of Earth surface scientists, trained within an international setting.

LIFE focuses its efforts on research related to Earth surface vulnerability in two key environments (watersheds and deltas) and implements its goals via the following closely linked programs: (1) Researcher exchange, (2) Shared and co-mentored postdoctoral researchers, (3) International shared graduate degree programs, (4) Theme-based focused research (mainly experimental and theoretical) campaigns, (5) International summer institutes for graduate students and young researchers, (6) Data/model sharing for actionable research, and (7) science-to-public international exchange.

Outreach

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

We have been featured in various public and scientific publications, e.g., Newsletter of the Scientific and technical Review Panel of the Ramsar Convention, (2013, Issue No 3) http://strp.ramsar.org/news-events/strp-newsletter/strp-newsletter-3-2013/strp-newsletter-3-2013

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.
3. Participation of students in the Summer Institute on Earth surface Dynamics (SIESD) which in 2014 is on complexity of depositional systems. This year co-PI Irina Overeem will present hands-on learning of the deltas modeling tools.
4. Participation of students and post-docs at the AGU and EGU meetings where the BF-DELTAS partners meet.

In 2015 we will plan the following major activities:

(1) Year 2 annual meeting (place TBD), which includes demonstration of BF-DELTAS results and engagement with stakeholders.
(2) Initiate stakeholder workshops at the other two case study sites (*Amazon and Ganges-Brahmaputra-Mehgna)* to assess how the Global Delta Vulnerability Index (GDVI) can be designed to be most useful for managers and decisions makers in these regions.
(3) Organize a special session at the EGU 2015 and AGU 2014 (session accepted) meetings.
(4) Coordination of major community campaigns that will include international participants (including BF-DELTAS participants) will be developed.
(5) Launch the "Sustainable Deltas 2015" Initiative with several satellite events and press conferences.

7. 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

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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.