Belmont Forum-G8 Collaborative Research:

BF-DELTAS:

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

Year 4 Progress Report to NSF: 2016-2017

Award Number: 1342944

Lead PI: Efi Foufoula-Georgiou (University of Minnesota)

A. ACCOMPLISHMENTS – What was done? What was learned?

1. What are the major goals of the project?

The overall goal of the BF-DELTAS project is to unify our scientific understanding of deltas as coupled socio-ecological systems and develop an integrative modeling framework that can be used to assess delta vulnerability and guide sustainable management and policy decisions at the regional and local scales.

The objectives of the project (termed "Work Packages" -WPs) are:

WP1 (**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.*

WP2 (**Delta-RADS**): *Develop an open-access, science-based, integrative modeling framework called the Delta Risk Assessment and Decision Support (RADS) Tool to support quantitative mapping of the bio-physical and socio-economic environment of deltas.*

WP3 (**Delta-DAT**): *Consolidate data on bio-physical, social, and economic parameters of deltas into a repository and make it readily available to the research and stakeholder community.*

WP4 (**Delta-**GDVI): *Develop Global Delta Vulnerability Indices that capture the current and projected physical-social-economic status of major deltas around the world ("delta vulnerability profiles").*

WP5 (**Delta-ACT**): Work with regional teams and stakeholders to *put the science, modeling, and data into action* by demonstrating their utility in three major deltas: the Ganges-Brahmaputra-Meghna (GBM), Mekong, and Amazon deltas.

2. What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

2.1. Major activities:

In the fourth year of the project, major activities included:

(1) Stakeholders and research meeting at the partner institution, The City University of New York (CUNY), in Sept 12-16, 2016 organized by the group of PI Charles Vorosmarty;
(2) BF-DELTAS project team meeting at the American Geophysical Union Fall meeting at San Francisco on December 17, 2016;
(3) An end-of-the-project meeting, as requested by the Belmont Forum, at the 2016 AGU Fall meeting on Dec 10-11, 2016;
(4) Four papers submitted by the team to a special issue on deltas in the journal *Sustainability Science* were shortlisted for the best paper in 2016. Total downloads: 7,929 downloads of 8 papers submitted from the project;
(5) Special issue on deltas in the journal *Elementa*, based on the meeting sessions on deltas organized by BF- DELTAS PIs at the 2015 AGU and 2016 AGU-JpGU meetings;
(6) Organization of *special sessions* at the AGU 2016 (Belmont forum projects session) and JpGU 2017 (deltas session) meetings.
(7) Several visits of PIs among BF-DELTAS participating institutions.

Some details of these activities are provided below.

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

Objectives: Belmont-Forum DELTAS project members and regional collaborators will share results of regional workshops; present new research results, tools, and data; plan for future funding opportunities and research projects; and produce a white-paper addressing our main findings and vision for future work.

Major questions:

- How do we assess, and address, delta human/ecological vulnerability?
- How important are coupled processes (climate, human, geological, biogeochemical, ecological, fluvial, oceanographic) in improving predictive delta models?
- What can we learn from remote sensing of deltas?
- Can we use our tools for decision support yet? What is still needed to do?
- How to best take advantage of remote sensing observations for delta research and decision support?

(2) BF DELTAS dinner meeting at the AGU Fall Meeting December 17, 2016 in San Francisco, California. The participants include Efi Foufoula-Georgiou, Alejandro Tejedor, Anthony Longjas, Irina Overeem, Tuhin Ghosh, Carol Wilson, Ryan Sincavage, Robert Nicholls, Atilla Lazar, Zoe Matthews, Kristine Nilsen, Fabrice Renaud, Manon Besset, Celine Grall, Zi Wu, Zach Tessler, and Juliette Baumann.

(3) An end-of-the-project meeting, as requested by the Belmont Forum, at the 2016 AGU Fall meeting on Dec 10-11, 2016. The BF Deltas team was represented by PIs Efi Foufoula-Georgiou, Robert Nicholls, Zoe Matthews, Fabrice Renaud, and Tuhin Ghosh.

(4) Four papers submitted by the team to the journal Sustainability Science were shortlisted for the best paper in 2016. Total downloads: 7,929 downloads of 8 papers submitted from the project.

- Renaud, F.G., Szabo, S. & Matthews, Z. Sustain Sci (2016) 11: 519. doi:10.1007/s11625-016-0380-6 (*Downloads: 1,300*)
- Tessler, Z.D., Vörösmarty, C.J., Grossberg, M. et al. Sustain Sci (2016) 11: 525. doi:10.1007/s11625-016-0357-5 (*Downloads: 1,200*)

- Szabo, S., Brondizio, E., Renaud, F.G. et al. Sustain Sci (2016) 11: 539. doi:10.1007/s11625-016-0372-6 (*Downloads: 2,100*)
- de Araujo Barbosa, C.C., Dearing, J., Szabo, S. et al. Sustain Sci (2016) 11: 555. doi:10.1007/s11625-016-0371-7 (*Downloads: 412*)
- Sebesvari, Z., Renaud, F.G., Haas, S. et al. Sustain Sci (2016) 11: 575. doi:10.1007/s11625-016-0366-4 (*Downloads: 723*)
- Brondizio, E.S., Vogt, N.D., Mansur, A.V. et al. Sustain Sci (2016) 11: 591. doi:10.1007/s11625-016-0368-2 (*Downloads: 548*)
- Vogt, N., Pinedo-Vasquez, M., Brondízio, E.S. et al. Sustain Sci (2016) 11: 611. doi:10.1007/s11625-015-0352-2 (*Downloads: 346*)
- Mansur, A.V., Brondízio, E.S., Roy, S. et al. Sustain Sci (2016) 11: 625. doi:10.1007/s11625-016-0355-7 (*Downloads: 1,300*)

(5) Special Issue in *Elementa* on 'Sustainable Deltas':

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

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

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

This Special Feature will be published in the multidisciplinary, nonprofit, open-access journal Elementa: Science of the Anthropocene.

Deadline for submissions is October 15th, 2016.

Guest editors:

Irina Overeem*, Community Surface Dynamics Modeling System, University of Colorado at Boulder*
Fabrice Renaud*, Institute for Environment and Human Security, United Nations University, Bonn*
Paola Passalacqua*, Dept. of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, USA*

(6) Special sessions at major meetings: Organization of *special sessions* at the AGU 2016 (Belmont forum projects session) and JpGU 2017 (deltas session) meetings.

(7) PI exchanges and Web collaboration ideas: PI Foufoula-Georgiou presented at the AGU 2016 and EGU 2017 meetings and met with BF-DELTAS partners present. The team also conducts regular cyber seminars and meetings for demonstration of modeling tools, discussion of data analysis and other concerns related to the project.

2.2. Significant Results

1. Entropy and optimality in river deltas

River deltas are critically important Earthscapes at the land water interface supporting dense populations and diverse ecosystems, while also providing disproportionally high food and energy resources. Yet, deltas are sinking at alarming rates due to sea level rise, local subsidence, and reduced sediment supply. Resilience to these perturbations depends on the structure of the deltaic channel network that ultimately dictates how water, sediment, and nutrients are spread over the delta surface. To date, however, a unified theory explaining how deltas self-organize to optimally distribute water and sediment up to the shoreline remains elusive. By defining a suitable Nonlocal Entropy Rate (based information theory concepts) and by analyzing data from field (Figure 1) and simulated deltas (Figure 2), we suggest that delta networks achieve configurations wherein the diversity of flux delivery to the shoreline is maximized. We suggest that prograding deltas attain dynamically accessible optima of the flux distributions for each configuration of their channel networks, thus effectively decoupling evolutionary timescales of geomorphology and hydrology. When interpreted in terms of delta resilience, high nonlocal Entropy Rate configurations reflect an increased ability to withstand perturbations but also suggest that the distributive mechanism responsible for dampening the perturbations, when exceeds a certain intensity threshold, might lead to catastrophic events.

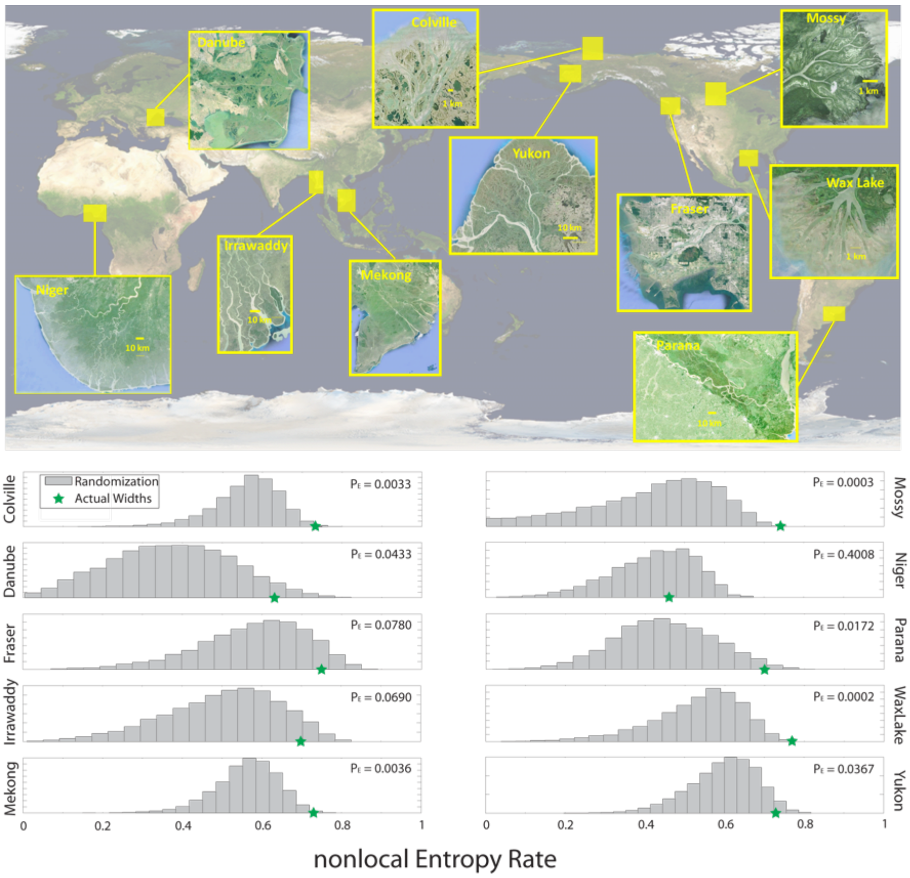


Figure 1. Nonlocal Entropy Rate for ten field deltas. Green stars represent the values of nonlocal Entropy Rate computed for ten field deltas, using channel width (extracted from Landsat) as proxy for flux partition in bifurcations. For comparison and as a null hypothesis, we have computed for each delta the values of nonlocal Entropy Rate when the flux partition is randomized. The results of 10^5 randomizations are displayed for each delta as histograms. It is observed that nine out of the ten deltas analyzed exhibit a maximal value of nonlocal Entropy Rate, supporting the hypothesis that deltas self-organize to maximize the diversity in delivering fluxes to the shoreline.

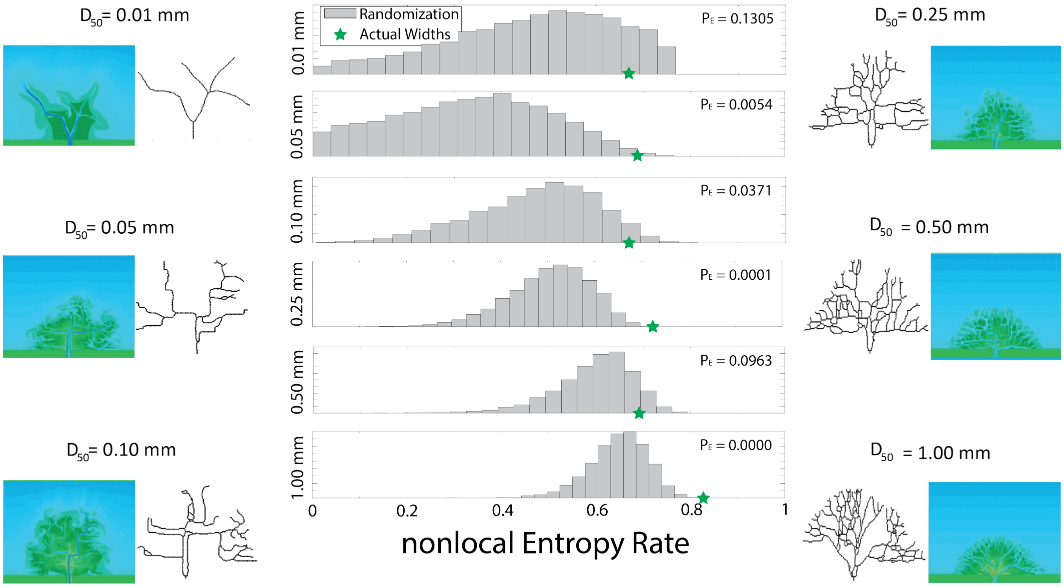


Figure 2. Nonlocal Entropy Rate for simulated deltas. We examine the nonlocal Entropy Rate of numerically simulated deltas obtained by the Delft3D model. The simulated deltas are river dominated, with no vegetation, and with a lognormal distribution of incoming sediment size with median grain-size D_{50} varying from 0.01 to 1.0 mm and the same variance in the log space. Similar to the analysis conducted for the field deltas, green stars represent the values of nonlocal Entropy Rate using channel width (extracted from simulations) as proxy for flux partition in each bifurcation. Five out of six deltas analyzed exhibit a maximal value of nonlocal Entropy Rate.

Publication:

Tejedor, A., A. Longjas, D. Edmonds, T. Georgiou, I. Zaliapin, A. Rinaldo, and E. Foufoula-Georgiou (2017), "Entropy and optimality in river deltas" Under Review, *Proceedings of the National Academy of Sciences USA*.

2. Passive microwave retrieval of flood inundation over deltas

Capturing the diurnal spatio-temporal dynamics of inundation over coastal regions, deltaic surfaces, and river floodplains requires high-resolution observations in both time and space, which are not available from the typical sparse ground-based sensors. Satellite observations from the visible to the microwave bands of the electromagnetic spectrum have been widely used for mapping floods, estimating surface water storages, river discharge values and water levels. In the visible bands (~0.4–0.8 μm), natural water reflects a fraction of incident light depending on the water depth and concentration of the optically active components such as suspended and dissolved particulate matter. However, water reflectivity sharply declines and approaches zero in the near infrared bands (~0.8–2.5 μm). Thresholding of this sharp gradient is often used to discriminate water bodies from their nearby dry soils and vegetated surfaces. In the microwave region of the spectrum, the dielectric constant of water (~80) is much higher than the dry soil (~4) and thus the inundated areas are substantially less emissive and radiometrically colder than the surrounding soils and vegetation covers. Moreover, emission from smooth water surfaces is more polarized than that from rough soils and vegetated surfaces. This polarization signal has also been used through empirical thresholding approaches to distinguish water surfaces from other land surface types. While visible and shortwave-infrared bands often provide sub-kilometer resolution for inundation mapping, their capability is very limited in a cloudy sky. This limitation is usually very restrictive over prone-to-flooding watersheds and deltas in tropical regions with high-frequency of heavy precipitation events.

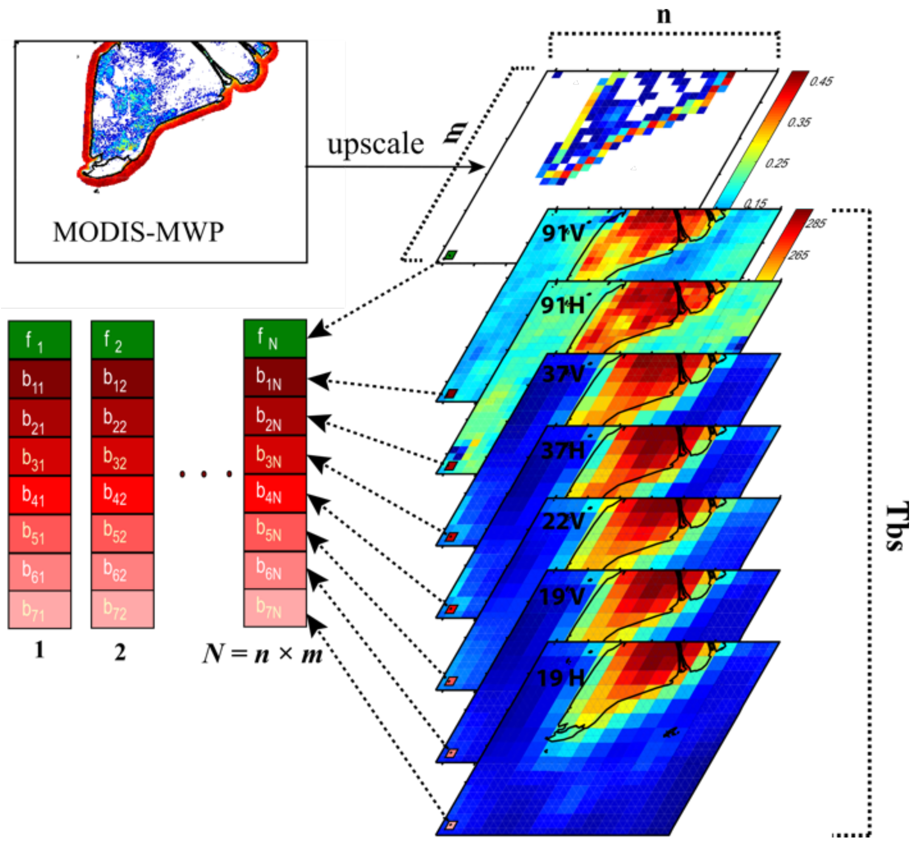


Figure 3. A Schematic showing construction steps of the a priori dataset for dictionaries. The top slab is the upscaled MODIS-MWP and the other slabs are the brightness temperature data at seven frequency bands. Each vector on the left is created by stacking a pixel-level information of the multi-frequency brightness temperatures by the SSMIS radiometer and their corresponding inundation fractions from the MWP product at 12.5 km resolution. This process is repeated for each orbit to generate a large number of vectors and form separate dictionaries for ascending and descending orbits using all satellite overpasses in 5 years from 2010 to 2014. $N = n \times m$ is the number of collected vectors for one day in a year. The same process is conducted for each day in 5 years (2010-2014) to create the dictionaries with $M = \sum_{i=1}^{365} N_i$ vectors.

We developed a multi-sensor Bayesian passive microwave retrieval algorithm for flood inundation mapping at high spatial and temporal resolutions. The algorithm takes advantage of observations from multiple sensors in optical, short-infrared, and microwave bands, thereby allowing detection and mapping of the sub-pixel fraction of inundated areas under almost all-sky conditions. The method relies on a nearest neighbor search and a modern sparsity-promoting inversion method that make use of an *a priori* dataset in the form of two joint dictionaries. These dictionaries contain almost overlapping observations by the Special Sensor Microwave Imager and Sounder (SSMIS) on board the Defense Meteorological Satellite Program (DMSP) F17 satellite and the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua and Terra satellites. Evaluation of the retrieval algorithm over the Mekong delta shows that it is capable of capturing to a good degree the inundation diurnal variability due to localized convective precipitation. At longer time-scales, the results demonstrate consistency with the ground-based water level observations, denoting that the method is properly capturing inundation seasonal patterns in response to regional monsoonal rain. The calculated Euclidean distance, rank-correlation and also Copula quantile analysis demonstrate a good agreement between the outputs of the algorithm and the observed water levels at monthly and daily time scales. The current inundation products are at resolution of 12.5 Km and twice per day, but higher resolution (order of 5 Km and every 3 hours) can be achieved using the same algorithm but populating the dictionary with the Global Precipitation Mission (GPM) Microwave Imager (GMI) products.

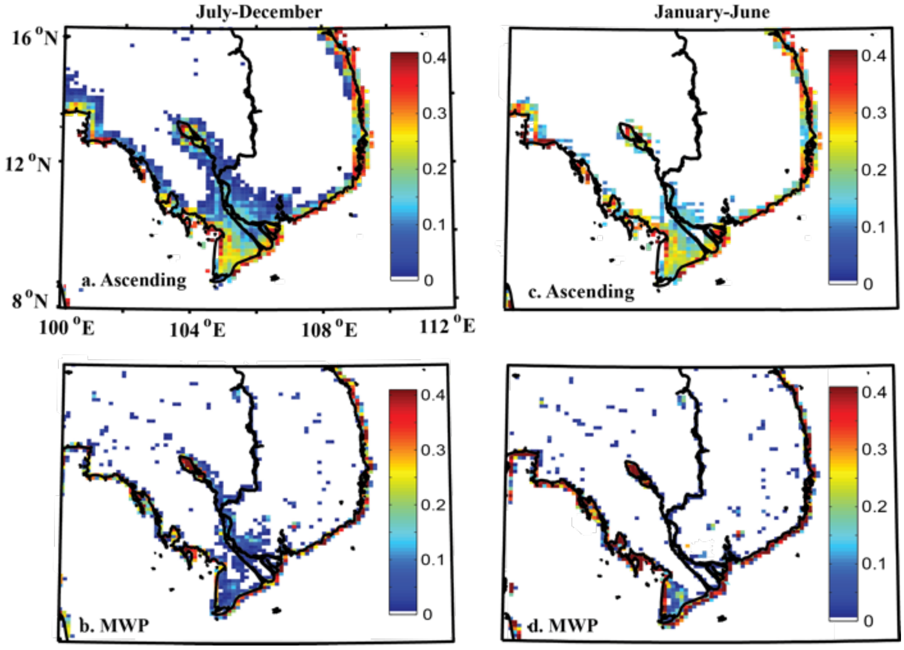


Figure 4. Inundated map of the Mekong delta in the wet (July-December) and dry (January-June) seasons for the ascending orbits. The results of the proposed retrieval algorithm are presented using the ascending dictionary (top row) against the upscaled MODIS Near Real-Time (NRT) Water Product (MWP) data (bottom row). Overall, a good agreement is observed with some overestimation of inundated areas by the proposed algorithm compared to MODIS-MWP data around the river banks.

Publication:

Takbiri, Z., A. M. Ebtehaj, and E. Foufoula-Georgiou, A Multi-sensor Data-driven methodology for all-sky Passive Microwave Inundation Retrieval, *Hydrologic and Earth System Science*, to appear, 2017.

3. Unravelling the association between the impact of natural hazards and household poverty: evidence from the Indian Sundurban delta

Coastal regions have long been settled by humans due to their abundant resources for livelihoods, including agriculture, transportation, and rich biodiversity. However, natural and anthropogenic factors, such as climate change and sea-level rise, and land subsidence, population pressure, developmental activities, pose threats to coastal sustainability. Natural hazards, such as fluvial or coastal floods, impact poorer and more vulnerable communities greater than more affluent communities. Quantitative assessments of how natural hazards affect vulnerable communities in deltaic regions are still limited, hampering the design of effective management strategies to increase household and community resilience. Drawing from Driving Forces–Pressure–State–Impact–Response (DPSIR), we quantify the associations between household poverty and the likelihood of material and human loss following a natural hazard using new survey data from 783 households within Indian Sundarban Delta community. The results suggest that the poorest households are significantly more likely to endure material and human losses following a natural hazard and repeated losses of livelihood make them more vulnerable to future risk. The results further suggest that salinization, tidal surge, erosion, and household location are also significant predictors of economic and human losses. Given the current and projected impact of climate change and importance of delta regions as the world's food baskets, poverty reduction and increase societal resilience should be a primary pathway to strengthen the resilience of the poorest populations inhabiting deltas.

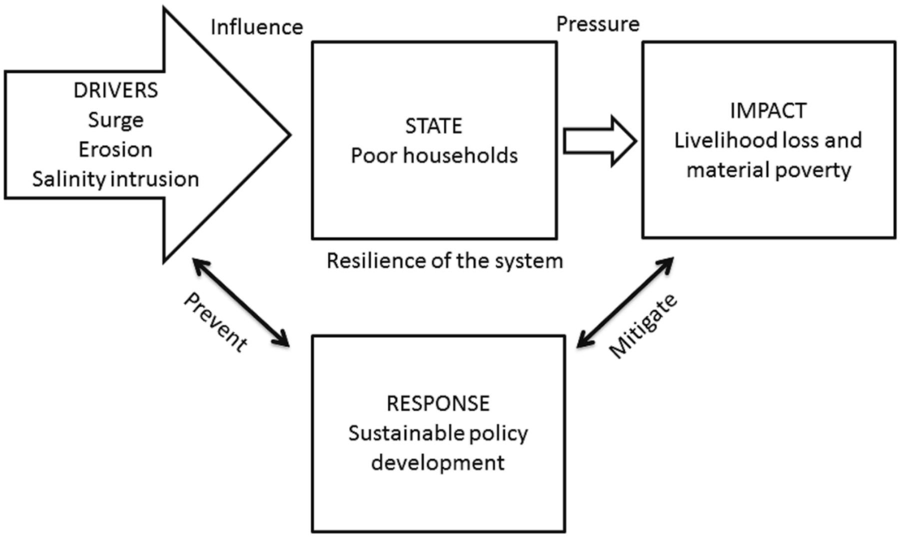


Figure 5. Conceptual framework adapted from the Driving Forces-Pressure-State-Impact-Response approach

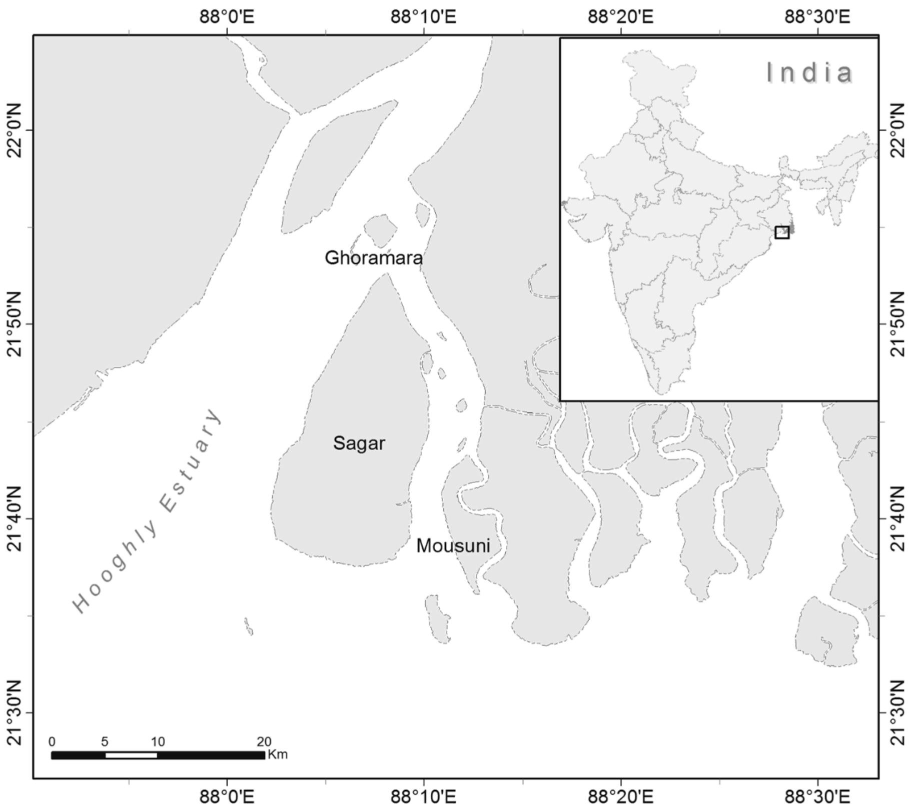


Figure 6. Study area. (Source: School of Oceanographic Studies, Jadavpur University)

Publication:

Hajra, R., S. Szabo, Z. Tessler, T. Ghosh, Z. Matthews, and E. Foufoula-Georgiou, Unravelling the association between the impact of natural hazards and household poverty: evidence from the Indian Sundurban delta, *Sustainability Science*, doi:10.1007/s11625-016-0420-2, 2017.

3. What opportunities for training and professional development has the project provided?

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

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

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

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

(3) Participation of students and postdocs in the Summer Institute on Earth surface Dynamics (SIESD), which in 2017 will focus on investigating scale in earth-surface systems to better inform predictions. The themes of scale at SIESD will concentrate on two main applications: earthcasting – the simulation of large-scale earth-system interactions; and river deltas – a nexus of climate, land, ocean, and society. PIs Efi Foufoula-Georgiou, Irina Overeem, Carol Wilson and Alejandro Tejedor will give lectures on deltas.

(4) Participation of students and post-docs at the AGU 2016, EGU 2017 and CSDMS 2017 meetings where the BF-DELTAS partners meet.

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

4. How have the results been disseminated to communities of interest?

(1) PI Eduardo Brondizio published an article in the Nature of Cities blog:

- The Elephant in the Room: Amazonian Cities Deserve More Attention in Climate Change and Sustainability Discussions

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

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

(3) Belmont Forum project brochure/newsletter featuring researchers and stakeholders addressing coastal vulnerability and freshwater security.

Steffen Gephardt

Eroding coastline of the Mekong Delta.

Increasing sustainability of coastal deltas in Bangladesh, Brazil, and Vietnam (DELTAS)

Deltas are bread baskets for large global areas, and are also complex, fragile social-ecological systems. The fragility of these systems and uncertainties around climate change impacts mean that unique ecosystems and millions of people are under threat. The DELTAS Project tackled this complexity by working together across disciplines and with key local stakeholders in the Amazon, Mekong, and Ganges-Brahmaputra deltas to develop comprehensive risk assessment frameworks which incorporate environmental, physical and social indicators and are applicable to deltas globally. The DELTAS approach can be adopted for other vulnerable areas, including drylands, glaciers, and urban areas to analyze contemporary and future risks and explore scenarios for risk-reducing investments.

(4) *Minute Earth: Why Do Rivers Have Deltas?*

https://www.youtube.com/watch?v=A47ythEcz74

Published on Dec 16, 2015

700,000+ views as of June 13, 2017

(5) *Science on a Sphere*

http://sos.noaa.gov/What_is_SOS/

(6) *River Delta animation*

http://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-10013/#gallery/25551

5. What do you plan to do during the next reporting period to accomplish the goals?

In Year 5 we will plan the following major activities:

(1) Development of a framework to analyze delta processes as directed coupled multilayer networks, that is networks in which different processes operate at different levels and there is interaction among layers.

(2) Implementation of this approach in understanding the system-wide effect of transport in channels and islands in deltaic systems, using data from Wax lake delta.

(3) Journal publications of the above results.

(4) Meeting with some of the BF-DELTAS project collaborators to discuss further synthesis of the project work.

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

(6) Research plans for next year are listed by each PI in their own reports submitted to NSF and for PI Foufoula-Georgiou in the attached pdf file which provides plan details on the major research themes of: (1) entropy and optimality in river deltas; (2) passive microwave retrieval of flood inundation over deltas; and (3) unravelling the association between the impact of natural hazards and household poverty from the Indian Sundurban delta.

Supporting Files

A file with more extensive research results for PI E. Foufoula-Georgiou is uploaded with this submission. Research results files of all other USA PIs are uploaded during their own NSF submission process to supplement the highlights and integrative efforts reported herein.

B. PRODUCTS – What has the project produced?

1. Publications (partially funded by this grant)

E. Foufoula-Georgiou

Belmont, P., and E. Foufoula-Georgiou (2017), Solving water quality problems in agricultural landscapes: new approaches for these nonlinear, multiprocess, multiscale systems, *Water Resources Research, 53*, 2585-2590, doi: 10.1002/2017WR020839

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

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (2017), Interplay between spatially-explicit sediment sourcing, hierarchical river-network structure, and in-channel bed-material sediment transport and storage dynamics, *Journal of Geophysical Research – Earth Surface*, *122*(5), 1090-1120, doi:10.1002/2016JF003965.

Danesh-Yazdi, M., E. Foufoula-Georgiou, D. L. Karwan, and G. Botter (2016), Inferring Changes in Water Cycle Dynamics of Intensively Managed Landscapes via the Theory of Time-Variant Travel Time Distributions, *Water Resources Research*, *52,* doi:10.1002/2016WR019091.

Danesh-Yazdi, M., G. Botter, and E. Foufoula-Georgiou (2017), Time-Variant Lagrangian Transport Formulation Reduces Aggregation Bias of Water and Solute Mean Travel Time in Heterogeneous Catchments, *Geophys. Res. Lett.,* 44, doi:10.1002/2017GL073827.

Danesh-Yazdi, M., A. Tejedor, and E. Foufoula-Georgiou (2017), Self-Dissimilar Landscapes: Revealing the Signature of Geologic Constraints on Landscape Dissection via Topologic and Multi-Scale Analysis, *Geomorphology*, Accepted.

Fan, N., A. Singh, M. Guala, E. Foufoula-Georgiou, and B. Wu (2016), "Exploring a semimechanistic Episodic Langevin model for bed load transport: Emergence of normal and anomalous advection and diffusion regimes", *Water Resour. Res*., doi:10.1002/2015WR018023.

Foufoula-Georgiou, E., P. Belmont, P. Wilcock, K. Gran, J. C. Finlay, P. Kumar, J. A. Czuba, J. Schwenk, and Z. Takbiri (2016), Comment on "Climate and agricultural land use change impacts on streamflow in the upper midwestern United States" by Satish C. Gupta et al., *Water Resources Research*, 52, 7536–7539, doi:10.1002/2015WR018494.

Gangodagamage, C., E. Foufoula-Georgiou, S.P. Brumby, R. Chartrand, A. Koltunov, D. Liu, M. Cai, and S.L. Ustin (2016), "Wavelet-compressed representation of landscapes for hydrologic and geomorphologic applications", *IEEE Geoscience and Remote Sensing Letters*, *13*(4), 480-484, doi:10.1109/LGRS.2015.2513011.

Hajra, R., S. Szabo, Z. Tessler, T. Ghosh, Z. Matthews, and E. Foufoula-Georgiou (2017), "Unravelling the association between the impact of natural hazards and household poverty: evidence from the Indian Sundurban delta", *Sustainability Science*, doi:10.1007/s11625-016-0420-2.

Hansen, A.T., J.A. Czuba, J. Schwenk, A. Longjas, M. Danesh-Yazdi, D. Hornbach, and E. Foufoula-Georgiou (2016), "Coupling freshwater mussel ecology and river dynamics using a simplified dynamic interaction model", *Freshwater Science*, *35*(1), 200-215, doi:10.1086/684223.

Kelly, S., Z. Takbiri, P. Belmont, and E. Foufoula-Georgiou (2017), "Human amplified changes in precipitation-runoff patterns in large river basins of the Midwestern United States", *Hydrology and Earth System Sciences*, In Revision, doi:10.5194/hess-2017-133.

Parodi, A., D. Kranzlmueller, A. Clematis, E. Danovaro, A. Galizia, L. Garrote, M. Llasat, O. Caumont, E. Richard, Q. Harpham, F. Siccardi, L. Ferraris, N. Rebora, F. Delogu, E. Fiori, L. Molini, E. Foufoula-Georgiou, and D. D'Agostino (2017), "DRIHM(2US): an e-Science environment for hydro-meteorological research on high impact weather events", *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-16-0279.1.

Schwenk, J., A. Khandelwal, M. Fratkin, V. Kumar, and E. Foufoula-Georgiou (2017), "High spatio-temporal resolution of river planform dynamics from Landsat: the RivMAP toolbox and results from the Ucayali River", *Earth and Space Science, 4,* 46-75, doi: 10.1002/2016EA000196.

Schwenk, J., and E. Foufoula-Georgiou (2016), "Meander cutoffs nonlocally accelerate upstream and downstream migration and channel widening", *Geophysical Research Letters*, 43, 12,4370-12,445, doi:10.1002/2016GL071670.

Schwenk, J., and E. Foufoula-Georgiou (2017), "Are process nonlinearities encoded in meandering river planform morphology?", *JGR Earth Surface*, Under Review.

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

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

Szabo, S., R.J. Nicholls, B. Neumann, F.G. Renaud, Z. Matthews, Z. Sebesvari, A. AghaKouchak, R. Bales, C.W. Ruktanonchai, J. Kloos, E. Foufoula-Georgiou, P. Wester, M. New, J. Rhyner, and C. Hutton (2016), "Making SDGs Work for Climate Change Hotspots", *Environment: Science And Policy For Sustainable Development*, 58:6, 24-33.

Takbiri, Z., A. M. Ebtehaj, and E. Foufoula-Georgiou, A Multi-sensor Data-driven methodology for all-sky Passive Microwave Inundation Retrieval, In Review, *Hydrology and Earth System Sciences*.

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

Tejedor, A., A. Longjas, D. Edmonds, T. Georgiou, I. Zaliapin, A. Rinaldo, and E. Foufoula-Georgiou (2017), "Entropy and optimality in river deltas" Under Review, *Proceedings of the National Academy of Sciences USA*.

Tejedor, A., A. Longjas, I. Zaliapin, S. Ambroj, and E. Foufoula-Georgiou (2017), "Network robustness assessed within a dual connectivity perspective" In Revision, *Scientific Reports*.

Tejedor, A., A. Singh, I. Zaliapin, A.L. Densmore, and E. Foufoula-Georgiou, Geomorphic Reorganization of Landscapes under Climate Change, In Review, Science Advances.

2. Presentations

Czuba, J.A., A. T. Hansen, E. Foufoula-Georgiou, and J. C. Finlay (2016), "Contextualizing Wetlands within a River-Network Perspective for Assessing Nitrate Removal at the Watershed Scale", H42G-05, AGU Fall Meeting, San Francisco.

Danesh-Yazdi, M., E. Foufoula-Georgiou and G. Botter (2016), "Accounting for catchment spatial heterogeneity via a time-variant Lagrangian transport formulation in estimating water and solute travel time distributions", B32A-04, AGU Fall Meeting, San Francisco.

Ebtehaj, A., and E. Foufoula-Georgiou (2016), "Towards better understanding of high-mountain cryosphere changes using GPM data: A Joint Snowfall and Snow-cover Passive Microwave Retrieval Algorithm", H23F-1608, AGU Fall Meeting, San Francisco.

Foufoula-Georgiou, E. (2016), "Climate and Humans as Amplifiers of Hydro-Ecologic Change: Science and Policy Implications for Intensively Managed Landscapes", Robert E. Horton Lecture, AMS Annual Meeting, New Orleans, Louisiana, 10-14 Jan. [**AWARDEE**]

Foufoula-Georgiou, E., and M. Ebtehaj (2016), "Resolving extreme rainfall from space: a new class of algorithms for precipitation retrieval over radiometrically complex terrain and coastal areas", EGU2016-18518, EGU General Assembly, Vienna, Austria, 17-22 April. [**SOLICITED**]

Foufoula-Georgiou, E., A. Tejedor and A. Longjas (2016), "Delta channel network complexity for quantitative delta classification and vulnerability assessment", HCG11-09, JpGU Meeting, Chiba City, Japan, 22-26 May.

Foufoula-Georgiou, E., Z. D. Tessler, E. Brondizio, I. Overeem, F. Renaud, Z. Sebesvari, R.J. Nicholls, and E. Anthony (2016), "Catalyzing action towards the sustainability of deltas: deltas as integrated socio-ecological systems and sentinels of regional and global change" GC33E-01, AGU Fall Meeting, San Francisco [**INVITED**].

Guala, M., A. Singh, E. Wong, and E. Foufoula-Georgiou (2016), "Scaling and normalization of river bathymetry spectra and bedform velocity" EP53E-1031, AGU Fall Meeting, San Francisco.

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

Marra, W.A., A. Tejedor, E. A. Addink, E. Foufoula-Georgiou, and M. G. Kleinhans (2016), "Connectivity of Multi-Channel Fluvial Systems: A Comparison of Topology Metrics for Braided Rivers and Delta Networks" EP53A-0930, AGU Fall Meeting, San Francisco.

Papalexiou, S.M., A. AghaKouchak, and E. Foufoula-Georgiou (2016), "A global assessment of changes in extreme daily maximum temperature", GC11B-1150, AGU Fall Meeting, San Francisco.

Papalexiou, S.M., E. Foufoula-Georgiou, and A. AghaKouchack (2017), "Watch the tail! A story on extreme hourly precipitation", EGU2017-10444-1, EGU General Assembly, Vienna, Austria.

Schwenk, S., A. Khandelwal, M. Fratkin, V. Kumar, and E. Foufoula-Georgiou (2016), "The Secret Lives of Migrating Rivers" EP51A-0882, AGU Fall Meeting, San Francisco.

Schwenk, J., A. Khandelwal, M. Fratkin, V. Kumar, and E. Foufoula-Georgiou (2017), "River morphodynamics from space: the Landsat frontier", EGU2017-11858, EGU General Assembly, Vienna, Austria.

Schwenk, J., and E. Foufoula-Georgiou (2017), "A case of self-perturbation: channel responses to meander cutoffs in the Ucayali River, Peru", EGU2017-11817, EGU General Assembly, Vienna, Austria.

Singh, A., A. Tejedor, A. Densmore, and E. Foufoula-Georgiou (2016), **"**Landscape response to climate change: quantifying a regime shift in transport processes at the onset of re-organization", EGU2016-10233, EGU General Assembly, Vienna, Austria, 17-22 April.

Singh, A., A. Tejedor, J.-L. Grimaud, and E. Foufoula-Georgiou (2016), "Experimental investigation of the effect of climate change and tectonic anisotropy on landscape evolution", CSDMS-SEN Annual Meeting, Boulder, Colorado, 17-19 May.

Singh, A., A. Tejedor, C. Keylock, I. Zaliapin, and E. Foufoula-Georgiou (2016), "Landscape evolution and re-organization under steady and transient states: results from an experimental investigation", 31st IUGG Conference on Mathematical Geophysics, Paris, 6-10 June.

Singh, A., A. Tejedor, J.-L. Grimaud, I. Zaliapin, and E. Foufoula-Georgiou (2016), "Quantifying the scale- and process- dependent reorganization of landscape under climatic change: inferences from an experimental landscape" EP32A-08, AGU Fall Meeting, San Francisco.

Singh A., A. Tejedor, J.-L. Grimaud, and Efi Foufoula-Georgiou (2017), "Experimental evidence of landscape reorganization under changing external forcing: implications to climate-driven knickpoints", EGU2017-17359-1, EGU General Assembly, Vienna, Austria.

Takbiri, Z., A. Ebtehaj, and E. Foufoula-Georgiou (2016), "Inundation Retrieval Using Passive Microwave Observations", H23F-1624, AGU Fall Meeting, San Francisco.

Tejedor, A., A. Longjas, R. Caldwell, D. Edmonds, I. Zaliapin, and E. Foufoula-Georgiou (2016), "Moving beyond the Galloway diagrams for delta classification: A graph-theoretic approach", EGU General Assembly, Vienna, Austria, 17-22 April.

Tejedor, A., A. Longjas, I. Zaliapin, and E. Foufoula-Georgiou (2016), "An entropy-based quantification of delta channel network complexity", Workshop on Information Theory and the Earth Sciences, Schneefernerhaus, Germany, 25-27 April.

Tejedor, A., A. Longjas, and E. Foufoula-Georgiou (2016), "Quantifying delta complexity toward inference and classification", CSDMS-SEN Annual Meeting, Boulder, Colorado, 17-19 May.

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

Tejedor, A, A. Longjas, and E. Foufoula-Georgiou (2016), "River delta self-organization via entropy rate analysis" EP53A-0931, AGU Fall Meeting, San Francisco.

Tejedor, A., A. Longjas, and E. Foufoula-Georgiou (2017), "Is there a self-organization principle of river deltas?", EGU2017-11531, EGU General Assembly, Vienna, Austria.

Wu, Z., E. Foufoula-Georgiou, M. Guala, X. Fu, and G. Wang (2016), "A New Lagrangian Formulation of Bedload Transport Guided by Ensemble Statistics of Particle Velocities and Accelerations", EP53E-1018, AGU Fall Meeting, San Francisco.

Wu, Z., E. Foufoula-Georgiou, G. Parker, A. Singh, X. Fu, and G. Wang (2017), "Burial effects on bedload tracer transport", EGU2017-2677, EGU General Assembly, Vienna, Austria.

3. *Technologies or techniques*

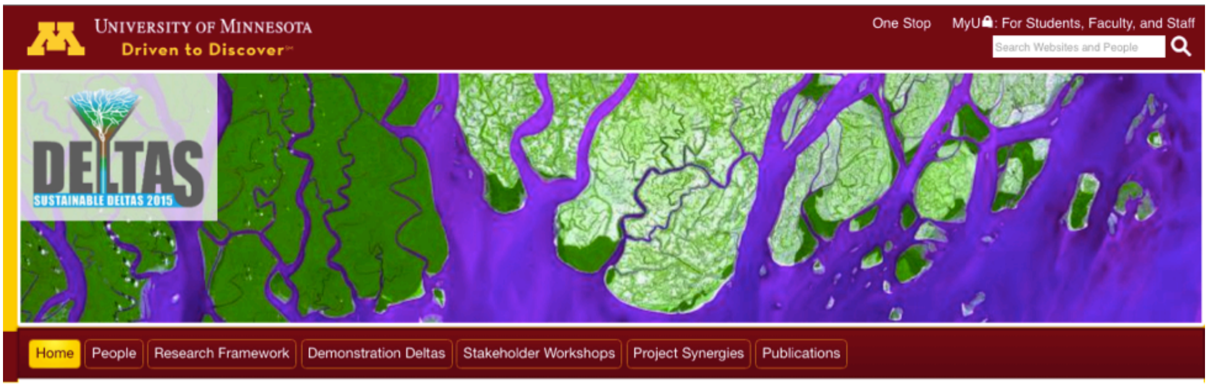
Not applicable

4. *Inventions, patent applications, and/or licenses*

Not applicable

5. *Websites*

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



6. Other products, such as data or databases, physical collections, audio or video products, software or NetWare, models, educational aids or curricula, instruments, or equipment

The iRODS ("Integrated Rule-Oriented Data System") data server is now used by the BF-DELTAS project. All information and resources generated by the BF-DELTAS project will be open-access and freely available to the world community. The stability and long-term archiving of the data is ensured because the data will be integrated into the programs and databases of project partners (e.g., NCED, CSDMS and IUCN and others) as well as programs of international environmental change initiatives such as LOICZ.

- *Minute Earth: Why Do Rivers Have Deltas?*

https://www.youtube.com/watch?v=A47ythEcz74

Published on Dec 16, 2015

700,000+ views as of June 13, 2017

- *Science on a Sphere*

http://sos.noaa.gov/What_is_SOS/

- *River Delta animation*

http://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-10013/#gallery/25551

- *Delta Modeling tools*

http://www.csdms.colorado.edu/wmt

C. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS – Who has been involved?

1. What individuals have worked on the project?

Efi Foufoula-Georgiou (PI)

Alejandro Tejedor (post-doctoral associate)

Anthony Longjas (post-doctoral associate)

International 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, I. Harrison, A. Tejedor and A. Longjas (University of Minnesota – Lead Institution); I. Overeem (University of Colorado at Boulder); S. Goodbred Jr. and Carol Wilson (Vanderbilt University); C. Vorosmarty and Z. Tessler (City College of New York); E. Brondizio (Indiana University)

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

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

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

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

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

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

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

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

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. What other organizations have been involved as partners?

Please see above (under International project team)

3. Have other collaborators or contacts been involved?

Please see above (under International project team)

D. IMPACT – What is the impact of the project? How has it contributed?

1. What is the impact on the development of the principal discipline(s) of the project?

BF-DELTAS is advancing the state of the art in understanding deltaic systems in an integrated way including geomorphology, hydrology, ecology and socio-demographic analysis. The researches of the PI have contributed original ideas to: (1) entropy and optimality in river deltas; (2) passive microwave retrieval of flood inundation over deltas; and (3) unravelling the association between the impact of natural hazards and household poverty from the Indian Sundurban delta.

2. What is the impact on other disciplines?

The network-based framework can be extended to a "multilayer networks" approach (beyond channels) to model surface to sub-surface flux exchange, nutrient transport, and ecological processes on deltas using graph theoretic approaches. It can also be used for analysis in other disciplines, e.g., socio-demographic networks, environment networks or even spatially variable processes which can be analyzed via connectivity ideas.

3. What is the impact on the development of human resources?

The BF-DELTAS team harnesses the collaboration of several, international and diverse teams of specialists with expertise in physical and social sciences, economics, health and demographics. Students and young researchers are exposed to an interdisciplinary approach to scientific research and a combination of theoretical approaches, models, fieldwork and survey-based analyses.

The delta risk framework combines physical, socio-economic and government aspects into integrated indices of risk and can be extended to other systems beyond deltas.

4. What is the impact on physical resources that form infrastructure?

Not applicable

5. What is the impact on institutional resources that form infrastructure?

Not applicable

6. What is the impact on information resources that form infrastructure?

Not applicable

7. What is the impact on technology transfer?

Not applicable

8. What is the impact on society beyond science and technology?

Delta research is immediately relevant to the livelihood of people that live there and the goods that they produce. A science-based integrative modeling framework that can be used to assess delta vulnerability and guide sustainable management and policy decisions on delta sustainability under human and climate stressors is socially important.

E. CHANGES/PROBLEMS

Notifications and Request

1. Changes in approach and reasons for change

None

2. Actual or Anticipated problems or delays and actions or plans to resolve them

None

3. Changes that have significant impact on expenditures

None

4. Significant changes in use or care of human subjects

None

5. Significant changes in use or care of vertebrate animals

None

6. Significant changes in use or care of biohazards

None

F. SPECIAL REQUIREMENTS

None

Supporting Files

You may also upload PDF files in support of this section. Please note, the maximum size allowed for upload is 10MB. Description (required if uploading a file).