Belmont Forum-G8 Collaborative Research:

BF-DELTAS:

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

Final (Year 5) Progress Report to NSF: 2017-2018

Award Number: 1342944

Lead PI: Efi Foufoula-Georgiou (University of California, Irvine)

https://delta.umn.edu/

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:

The project developed (1) vulnerability and risk assessments frameworks for deltaic socio-ecological systems at multiple scales (global, network-based, local); (2) Delta Resilience Tools that advanced the science and open access transferable tools to aid decision support; (3) integrated multi-sensor remote sensing and in-situ observations for modeling, real-time assessment, and forecasting; (4) showed trade-offs between human and natural processes in future risk assessment and effective management.

The project (13 PIs in 13 institutions) spearheaded the ICSU Sustainable Deltas Initiative 2015 (SD2015). It has resulted in more than 75 publications, two special issues in the journals "Sustainability Science" and "Elementa: Deltas in the Anthropocene", one Science Brief on the Sustainable Development Goals (SDGs), and organization of *special deltas sessions* at the AGU 2016, EGU 2016 and JpGU 2016 meetings. The US part of the project trained 8 postdocs and 5 graduate students. Through multiple extensive workshops with stakeholders, policy makers and local experts in the Amazon, Mekong and Ganges Brahmaputra deltas we developed tools for delta vulnerability and risk assessment and analyzed scenarios of change that included a range of socio-ecological factors particular to each delta.

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

(1) The *Summer Institute on Earth surface Dynamics* (SIESD 2018) focusing on "Earth-surface math: evolution, signals, and connections" to be hosted at the *St. Anthony Falls Laboratory, University of Minnesota on July 25th-August 4th, 2018.* Approximately 40 students from all over the world were accepted to the SIESD 2018 *and the top 2 international applicants were offered partial travel support from BF DELTAS as needed, to enable their participation.*

(2) Several visits of PIs among BF-DELTAS participating institutions.

Some details of these activities are provided below.

(1) SIESD 2018: Earth-surface math: evolution, signals, and connections. Summer Institute on Earth-surface Dynamics (SIESD) 2018 to be held on July 25th-August 4th, 2018 at the St. Anthony Falls Laboratory, University of Minnesota: This year's Summer Institute focuses on the mathematical tools involved in earthcasting, with a particular focus on landscape connections and how signals (e.g. effects of climate change) are propagated through Earth-surface systems and recorded, whether in deposits or the current landscape. A desire to learn is essential, but training in advanced mathematics is not. The topics to be explored will include both erosional and depositional landscapes. Lectures and exercises on mathematical techniques will be complemented by experiments and observations at the St. Anthony Falls Laboratory.

(2) PI exchanges and Web collaboration ideas: PI Foufoula-Georgiou and postdocs Alejandro Tejedor and Anthony Longjas presented at the AGU 2017, EGU 2018 and First SoCal Geomorphology Symposium 2018 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

2.2.1. ***Multiplex Networks: A framework for studying multi-process multi-scale connectivity via coupled-network theory with an application to river deltas.***

To investigate transport properties of multi-process multi-scale connected systems we introduce the framework of multilayer networks which allows to quantify properties of the system as a whole, not accessible by studying each system separately. We illustrate this framework by examining the flux dynamics in a river delta system, where channelized (within the channel network) and overland (on the islands) flows are considered. We represent the delta system as a two-layer multiplex, wherein each layer consists of the same number of nodes, but the connectivity among them is different and representative of each process. The degree of coupling among layers denotes the flux exchange in-between the two transport processes and in this study is driven by the discharge level, although a strong control is also exerted by the relative roughness of the islands (e.g., vegetation). To illustrate the potential of this framework, we investigate the timescale of convergence to the steady-state flux distribution for different degrees of coupling, revealing the existence of four different regimes: linear, sublinear, prime and asymptotic. We highlight that the prime regime, where the timescale of convergence to steady-state achieves its smallest value, occurs for intermediate values of coupling, i.e., not extreme values of discharge, where the redistribution of sediment and nutrients is the fastest across the delta top, enhancing the overall system aggradation and nourishment.

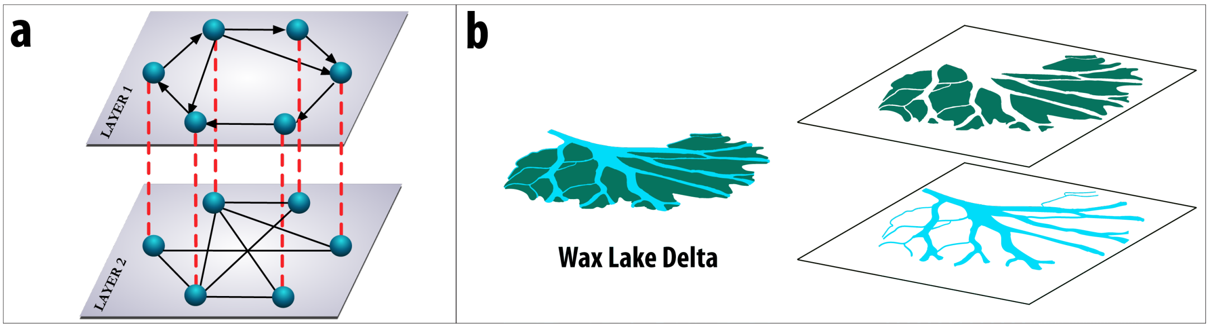

Figure 1. Delta Multiplex (a) *Illustration of a multiplex:* Multiplex are coupled multilayer networks where each layer consists of the same set of nodes but possibly different topologies (set of links), and layers interact with each other only via replica nodes in each layer (dashed lines) **(b)** *Wax Lake Delta Multiplex.* Illustration of the Wax Lake delta in the Louisiana coast (USA). The delta multiplex consists of two layers: Layer 1 (Bottom) accounts for the channel connectivity, and Layer 2 (Top) represents the connectivity that arises from overland flow on islands. For more details about the multiplex structure see supplementary materials.

The application of this framework to specific systems in a more detailed manner opens up interesting research questions such as (1) what is the return period of the discharge that corresponds to the optimal coupling (1-year event, 10-year event, etc.) and how does it affect the evolution of those systems and their resilience to extreme events, (2) what specific locations of a delta might amplify across-process connectivity critically affecting the overall system transport timescales; and (3) how is the system transport timescale dependent on including more or less refined specification of across-process connectivity? For instance, by accounting for vegetation, topography, etc., more layers can be included, with islands of similar characteristics (i.e., islands that can be modeled by a similar diffusion coefficient) grouped in the same layer. Finally, we want to emphasize the broad applicability of this framework to diverse fields in the geosciences where multi-process multi-scale interactions dictate the overall system behavior. Examples include flux transport taking into account surface-subsurface exchange, integrated wetland and river systems, interaction types among species in ecological systems, climate networks, etc.

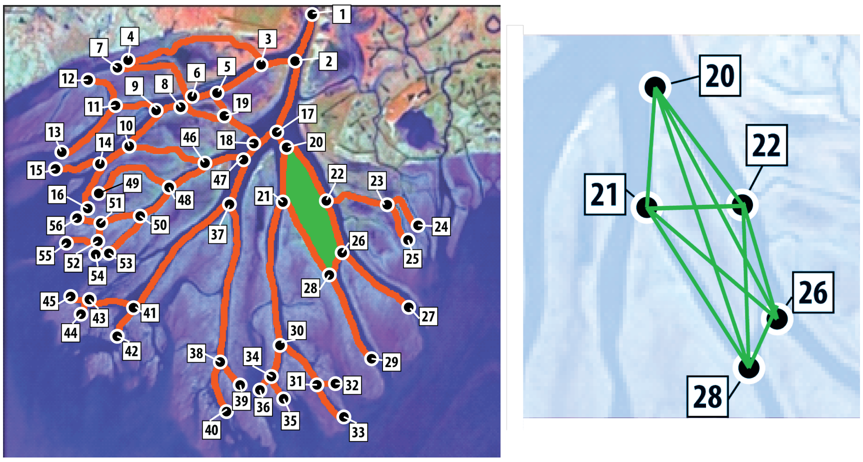

Figure 2. Wax Lake Multiplex Network. Wax Lake delta in the Louisiana coast. **(Left)** Delta Channel Network (DCN): The DCN (nodes as black circles and links as yellow lines) is superimposed on the aerial view of the delta (photo obtained in 2005 by the National Center of Earth-surface Dynamics, NCED). **(Right)** Delta Island Network (DIN): The DIN is displayed for one of the islands (island colored in green in the left panel). The islands network consists of the same set of nodes in the DCN, but the set of links (e.g., green lines) is different.

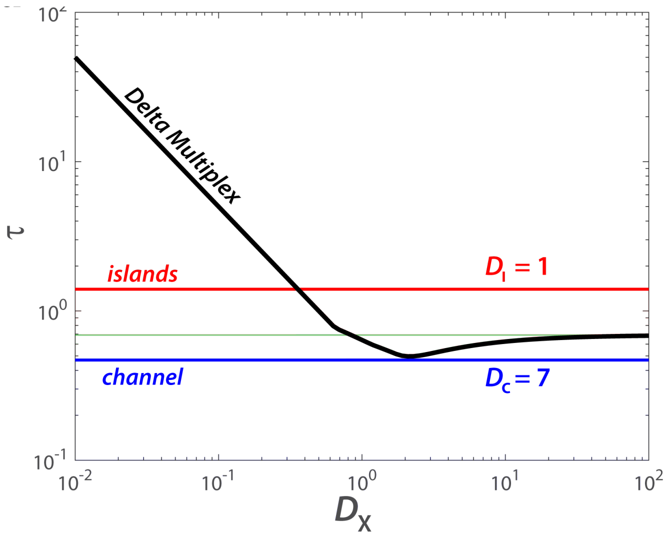

Figure 3. Flux Dynamics on the Wax Lake Delta Multiplex. We show for the Wax Lake multiplex, the timescale of convergence to steady-state, τ, as a function of interlayer coupling, D_X, which is mostly controlled by water discharge. Panel (a) shows the emergence of a non-monotonic behavior of τ as function of D_X, when the values of diffusivity of each layer are set to (D_C, D_I) = (7, 1) to reproduce the ratio of transport timescales channel to island reported from field campaigns.

Publication:

1. Tejedor, A., A. Longjas, P. Passalacqua, Y. Moreno and E. Foufoula-Georgiou, Multiplex Networks: A framework for studying multi-process multi-scale connectivity via coupled-network theory with an application to river deltas, In Revision, *Geophysical Research Letters*, 2018.

Presentations:

1. Tejedor, A., A. Longjas, and E. Foufoula-Georgiou (2017), Modeling multi-process connectivity in river deltas: extending the single layer network analysis to a coupled multilayer network framework, EP52A-06, AGU Fall Meeting, New Orleans. **(INVITED)**
2. Longjas, A., A. Tejedor, and E. Foufoula-Georgiou (2018), River deltas as Multiplex networks: A framework for studying multi-process multi-scale connectivity via coupled-network theory, Earth's Dynamic Landscapes: First Annual SoCal Geomorphology Symposium, Caltech, Pasadena, California.

2.2.2. *Diffusion Dynamics and Optimal Coupling in Multiplex Networks with Directed Layers*

We revealed the existence of a prime regime in which directed multiplex networks may exhibit a faster system-wide diffusion for intermediate values of coupling than in the asymptotic limit, when the different layers are fully coupled. Within that regime there is an optimal value of coupling at which the diffusion is the fastest, i.e., the time scale of convergence to steady state is minimum. Furthermore, the rates of diffusion in multiplex configurations where the prime regime is exhibited can be such that a new superdiffusion regime emerges, where the multiplex diffusivity as a whole is faster than that of the fastest of its layers for intermediate values of coupling. We argue that it is precisely the directionality of paths at the network scale that sets an anisotropic layout for the process, and combined with a balance of (1) significant connectivity across layers (making accessible paths in other layers) and (2) a degree of independence in the intralayer dynamics, can catalyze the overall system transport dynamics.

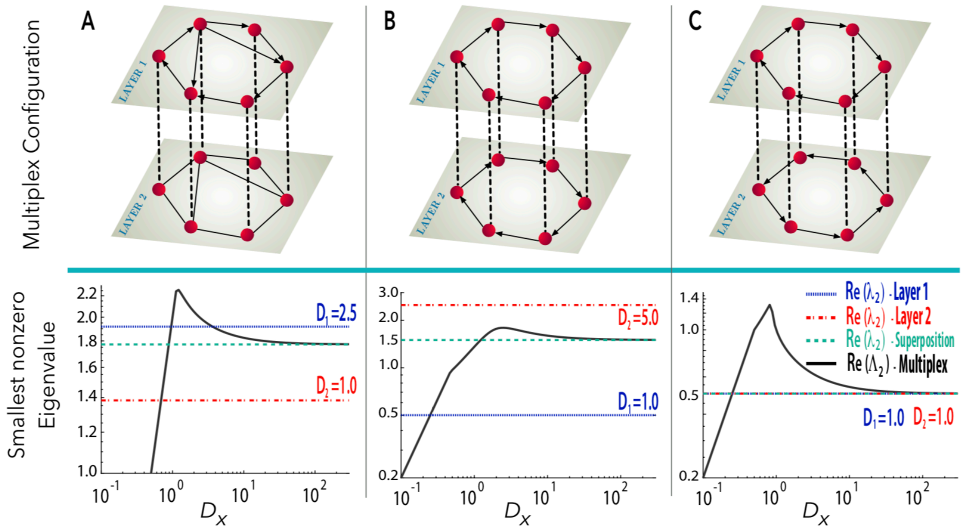

Figure 1. The top panels depict the three synthetic multiplex networks with two coupled layers discussed in the text: (a) corresponds to Multiplex-1; (b) to the Multiplex-2 configuration; and (c) to the Multiplex-3 architecture. Bottom panels show the behavior of the smallest (in terms of its real part) nonzero eigenvalue $\mathrm{Re}(\Lambda_2)$ of the supra-Laplacian L^{out} as a function of interlayer coupling, D_X.

Using synthetic and real-world multiplex networks, we showed how a sufficient degree of network-scale directionality in the directed layer is a necessary condition for the emergence of the prime regime. We proved analytically that undirected multiplex do not exhibit a prime regime for intermediate couplings and their rate of convergence to steady state is a monotonically increasing function of the interlayer coupling. Thus, the extrapolation of the expectation from previous results on dynamics on undirected multiplex networks, wherein diffusion processes achieve the fastest rate of convergence to steady state when the different layers are fully coupled, generally leads to a wrong assessment of system dynamics. Our results open up new paths of research addressing questions such as whether natural complex systems self-organize to configurations where the optimal coupling is accessible to their dynamics. We also believe that extending this study to other real settings might have important implications. For instance, many social or techno-social networks (like Online Social Networks) have many directed relationships -- i.e., following-follower relations are not always reciprocal or symmetric -- which make them good candidates to observe the phenomenology here described. Alternatively, our results could also inspire the design of directed multilayer networks in which directionality is exploited so as to make these systems operate in a regime in which the optimal coupling is reachable for the dynamics.

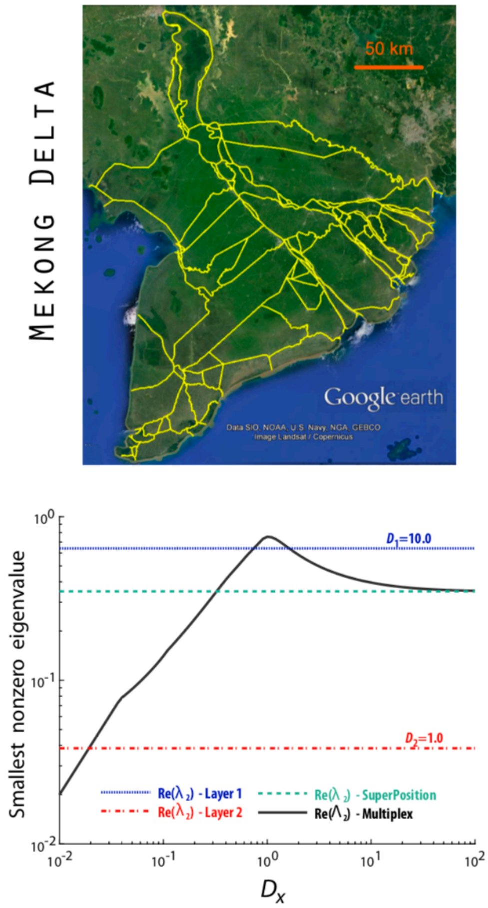

Figure 2. The Mekong delta Multiplex. The top panel shows the extracted channel network of the Mekong delta at 50 m resolution. The bottom panel shows the behavior of the smallest (in terms of its real part) nonzero eigenvalue Re($\Lambda 2$) of the supra-Laplacian L^{out} corresponding to the Mekong delta multiplex as a function of D_X . For intermediate coupling rates, $D_X \sim 1$, maximum Re(Λ_2) is observed.

Publication:

1. Tejedor, A., A. Longjas, E. Foufoula-Georgiou, T. Georgiou, and Y. Moreno, Diffusion Dynamics and Optimal Coupling in Multiplex Networks with Directed Layers, In Revision, *Physical Review X*, 2018.

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.

(3) Participation of students and postdocs in the Summer Institute on Earth surface Dynamics (SIESD), which in 2018 will focus on investigating scale in earth-surface systems to better inform predictions. The themes of scale at SIESD will focus on the mathematical tools involved in earthcasting, with a particular focus on landscape connections and how signals (e.g. effects of climate change) are propagated through Earth-surface systems and recorded, whether in deposits or the current landscape. PIs Efi Foufoula-Georgiou, Irina Overeem,

Carol Wilson and postdoc Alejandro Tejedor will give lectures on deltas.

(4) Participation of students and post-docs at the AGU 2017, EGU 2018 and CSDMS 2018, and SoCal Geomorphology Symposium 2018 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) Belmont Forum project brochure/newsletter featuring researchers and stakeholders addressing coastal vulnerability and freshwater security.

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.

Steffen Gephardt

Eroding coastline of the Mekong Delta.

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

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

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

Published on Dec 16, 2015

1,137,534 views as of July 9, 2018

(3) *Science on a Sphere*

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

(4) *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?

NONE

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. Dissertation

Zeinab Takbiri (2018), "Multi-satellite remote sensing of land-atmosphere interactions: Advanced data-driven methodologies for passive microwave retrievals of precipitation and flood," University of Minnesota. Supervised by BF DELTAS PI Foufoula-Georgiou.

2. Publications

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.

Takbiri, Z., A. M. Ebtehaj, and E. Foufoula-Georgiou (2017), A Multi-sensor Data-driven methodology for all-sky Passive Microwave Inundation Retrieval, *Hydrology and Earth System Sciences*.

Tejedor, A., A. Longjas, D. A. Edmonds, I. Zaliapin, T. Georgiou, A. Rinaldo, and E. Foufoula-Georgiou, Entropy and optimality in river deltas, *Proceedings of the National Academy of Sciences, USA*, 114(44), 11651-11656, doi:10.1073/pnas.1708404114, 2017.

Tejedor, A., A. Longjas, I. Zaliapin, S. Ambroj, and E. Foufoula-Georgiou, Network robustness assessed within a dual connectivity framework: joint dynamics of the Active and Idle Networks, *Scientific Reports* 7, 8567, doi:10.1038/s41598-017-08714-3, 2017.

Tejedor, A., A. Singh, I. Zaliapin, A.L. Densmore, and E. Foufoula-Georgiou, Geomorphic Reorganization of Landscapes under Climate Change, *Science Advances*, 2017.

Tejedor, A., A. Longjas, E. Foufoula-Georgiou, T. Georgiou, and Y. Moreno, Diffusion Dynamics and Optimal Coupling in Directed Multiplex Networks, In revision, 2018.

Tejedor, A., A. Longjas, P. Passalacqua, Y. Moreno, and E. Foufoula-Georgiou, River deltas as Multiplex networks: A framework for studying multi-process multi-scale connectivity via coupled-network theory, In revision, 2018.

Longjas, A., A. Tejedor, and E. Foufoula-Georgiou, Inferences on predator-prey vulnerabilities via spectral graph analysis of food webs, In revision, 2018.

3. Presentations

Foufoula-Georgiou, E. (2017), Environmental sustainability at the intersection of climate and human change, Caltech Division of Geological and Planetary Sciences, November 15, 2017. (INVITED)

Foufoula-Georgiou, E. (2018), Environmental sustainability at the intersection of climate and human change, UCLA Department of Earth, Planetary, and Space Sciences, January 23, 2018. (INVITED)

Tejedor, A., A. Longjas, and E. Foufoula-Georgiou (2017), Modeling multi-process connectivity in river deltas: extending the single layer network analysis to a coupled multilayer network framework, EP52A-06, AGU Fall Meeting, New Orleans. **(INVITED)**

Tejedor, A., A. Longjas, D.A. Edmonds, I. Zaliapin, T.T. Georgiou, A. Rinaldo, and E. Foufoula-Georgiou (2017), Optimality and self-organization in river deltas, EP13D-07, AGU Fall Meeting, New Orleans.

Longjas, A., A. Tejedor, E. Foufoula-Georgiou (2017), Graph Theory Approach for Studying Food Webs, IN33B-0119, AGU Fall Meeting, New Orleans.

Vulis, L. and E. Foufoula-Georgiou (2018), Channel-Lake Connectivity in Arctic Deltas, Earth's Dynamic Landscapes: First Annual SoCal Geomorphology Symposium, Caltech, Pasadena, California.

Longjas, A., A. Tejedor, and E. Foufoula-Georgiou (2018), River deltas as Multiplex networks: A framework for studying multi-process multi-scale connectivity via coupled-network theory, Earth's Dynamic Landscapes: First Annual SoCal Geomorphology Symposium, Caltech, Pasadena, California.

Tejedor, A., A. Longjas and E. Foufoula-Georgiou (2018), An optimality principle underlaying self-organization of River Deltas, Earth's Dynamic Landscapes: First Annual SoCal Geomorphology Symposium, Caltech, Pasadena, California.

4. Technologies or techniques

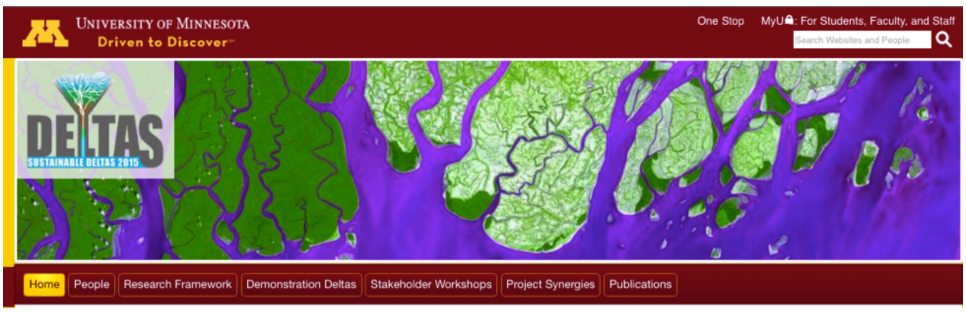
Not applicable

5. Inventions, patent applications, and/or licenses

Not applicable

6. 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

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

https://www.youtube.com/watch?v=A47ythEcz74
Published on Dec 16, 2015; 1,137,534 views as of July 9, 2018

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)

<u>D. IMPACT</u> – 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) *Multiplex Networks: A framework for studying multi-process multi-scale connectivity via coupled-network theory with an application to river deltas*, and (2) *Diffusion Dynamics and Optimal Coupling in Multiplex Networks with Directed Layers*.

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).