NSF Water Sustainability and Climate (WSC) project EAR-1209402

REACH (REsilience under Accelerated CHange)

Year 4 Progress Report for 2015–2016

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

1.1. What are the major goals of the project?

The overall goal of our Water Sustainability and Climate project (called REACH: REsilience under Accelerated CHange) is to develop a framework within which the vulnerabilities of a natural-human system can be assessed to guide decision-making towards eco-hydrologic sustainability and resilience. A unique element of the developed framework is identifying and focusing on places, times, and processes of accelerated or amplified change. One specific hypothesis to be tested is that of Human Amplified Natural Change (HANC), which states that areas of the landscape that are most susceptible to human, climatic, and other external changes are those that are undergoing the highest natural rates of change. To test the HANC hypothesis and turn it into a useful paradigm for enabling water sustainability studies, a predictive understanding of the cascade of changes and local amplifications between climatic, human, hydrologic, geomorphologic, and biologic processes are being developed to identify "hot spots" of sensitivity to change and inform mitigation activities.

The developed framework is being tested in the Minnesota River Basin (MRB) where geological history, climate variability, and intensive agriculture are affecting changes in water quantity, water quality, and ecosystem health.

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

1.2.1. Major activities:

(1) Research integration, collaboration, and dissemination

1. A 3-day annual collaboration meeting was held in August 2015 at the University of Minnesota in Minneapolis, MN, to bring PIs and their research groups together to discuss science integration and action plans for the next year.
2. 48 Presentations were given this past year at local, regional, national, and international conferences including: annual meetings of the American Geophysical Union, European Geosciences Union, National Association of Research in Science Teaching, American Meteorological Society, Japan Geophysical Union, Community Surface Dynamics Modeling System, Green School Conference and Expo; River Flow – International Conference on Fluvial Hydraulics; Symposium on River, Coastline, and Estuary Morphodynamics; IUGG Conference on Mathematical Geophysics; INQUA; International Environmental Youth Symposium, First American Land Consortorium, Institute on the Environment Sustainability Symposium, Upper Midwest Stream Restoration Symposium, Minnesota Water Resources Conference, Minnesota Quaternary Science meeting, Workshop on Information Theory and the Earth Sciences, Geology department at the University of Illinois, Waseca County Farmer Forum, and to the Water Resources group at Barr Engineering.

(2) Educational activities

The fourth year of the "The River Run: Professional Development with a Splash of Technology" has progressed toward the project's goals of continued research and development. "The River Run" is an effort to promote awareness in secondary science classrooms about issues related to the Minnesota River and its watershed for the communities in which the classrooms exist. On-going work is exploring the development of an interactive, online computer-simulation tool that allows students to explore the impact of land-management practices on nitrate levels. The basis for this computer-simulation tool is the research of REACH members. Additionally, we are reworking scientific articles related to the WSC scientific research into formats accessible for students and classroom use. Examples of developed curricula can be found on the project site at this link (http://stem-projects.umn.edu/riverrun/test-page/).

(3) Stakeholder meetings

Stakeholder meetings were held by multiple REACH PIs through the Collaboration for Sediment Source Reduction (CSSR) during August 2015 and January 2016 in Mankato, MN. Stakeholder meetings have continued from last year and provide a venue for disseminating results from research on the REACH project directly to federal, state, and county agency staff; growers associations; citizen activist groups; farmers; and other university and extension agency researchers. Attendees (~20-40 people) came from Minnesota Pollution Control Agency, Minnesota Department of Natural Resources, Minnesota Corn Growers Association, Minnesota Agricultural Water Resource Center, Blue Earth County, Greater Blue Earth River Basin Alliance, Minnesota Soybean Growers Association, University of Minnesota Extension Agency, University of Minnesota, Johns Hopkins University, Utah State University, North Dakota State University, and several farmers. One stakeholder meeting remains (Aug.-Oct. 2016), which will involve use of a reduced complexity water and sediment routing model to predict and weigh costs/benefits of various watershed management/restoration alternatives in light of the best available information.

1.2.2. Specific Objectives:

The project has four main objectives, on which significant progress has been made over the past 4 years, as described in the next section and the attached pdf document:

(1) Determine the extent to which current high rates of sediment production, amplified by land-use, hydrologic, and climate changes, are affected by the underlying geology and geomorphic history of the basin, guiding a topography-based predictive framework of sediment sourcing and budgeting in a dynamic landscape.

(2) Quantify how climate and land-use driven hydrologic change, amplifies and accelerates environmental and ecological change in the basin, and how nonlinearities and amplifications can be quantified and upscaled across basins of different size;

(3) Understand the interactions of the river network physical structure and biological processes, including the role of wetlands, lakes and riparian zones, in nutrient transport and cycling, phosphorous-sediment budgeting, and food web structure towards a predictive framework in highly dynamic agricultural landscapes;

(4) Propose conservation management strategies, including sediment and nutrient reduction, to sustain ecological health and species biodiversity while promoting economic development and agricultural productivity.

1.2.3. Significant results:

During 2015-2016, our research has been integrative along five major topical areas (*see attached pdf for a brief summary of these research topics*):

1. **Predictive framework of sediment sourcing and cycling in a coupled human-natural landscape**
    - 1.1. Dynamics of meandering rivers and inferring geomorphic processes from patterns
    - 1.2. Sediment dynamics on river networks

2. **Cascade of climate and land use/land cover change to eco-hydrologic change**
    - 2.1. Inferring changes in water cycle dynamics of intensively managed landscapes via the theory of time-variant travel time distributions
    - 2.2. Feedback between hydrologic change, riparian vegetation establishment, and floodplain dynamics
    - 2.3. Flow-related dynamics in suspended algal biomass and its contribution to suspended particulate matter

3. **Quantifying nutrient and phosphorus cycling in intensively managed landscapes**
    - 3.1. Anthropogenic and environmental controls on nutrient inputs and export

3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics
3.3. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes

4. **The role of wetlands and water-retention structures in environmental restoration of intensively managed landscapes**
   4.1. Modeling wetland restoration scenarios for targeted mitigation of peak flows
   4.2. Network structure nitrate removal efficiency
   4.3. Evaluation of trade-offs associated with wetland interventions

5. **Engaging and educating the public**
   5.1. Socio-scientific issues
   5.2. Curriculum development and classroom implementation

1.2.4. Key outcomes or other achievements:

The WSC REACH project is in synergy with two other projects: the new Intensively Managed Landscapes Critical Zone Observatory (IML-CZO) and the Collaborative for Sediment Source Reduction (CSSR).

Intensively Managed Landscapes Critical Zone Observatory (IML-CZO)

The Minnesota River Basin (MRB), which is the focus of our REACH project, became in 2013 part of the Intensively Managed Landscapes-Critical Zone Observatory (IML-CZO), led by REACH PI Praveen Kumar at the University of Illinois. The IML-CZO aims to understand the present-day dynamics of intensively managed landscapes in the context of long-term natural coevolution of the landscape, soil, and biota under significant land-use change mainly due to agriculture. The IML-CZO will enable us to assess the short- and long-term resilience of the crucial ecological, hydrological, and climatic "services" provided by the Critical Zone, the "skin" of the Earth that extends from the treetops to the bedrock. An observational network of three sites in Illinois, Iowa, and Minnesota that capture the geological diversity of the low-relief, post-glaciated, and tile-drained landscape will allow for novel scientific and technological advances in understanding the Critical Zone. The IML-CZO also provides leadership in developing the next generation of scientists and practitioners and in advancing management strategies aimed at reducing the vulnerability of the system to present and emerging trends in human activities.

The IML-CZO includes three sites—the 3,690-km^2 Upper Sangamon River Basin in Illinois, the 270-km^2 Clear Creek Watershed in Iowa, and the 44,000-km^2 Minnesota River Basin. These three sites, all characterized by low-relief landscapes with poorly drained soils, represent the broad range of physiographic variations found throughout the post-glaciated Midwest, and thereby provide an opportunity to advance understanding of the Critical Zone in this important region.

The IML-CZO Program is a joint effort by a growing team of faculty and scientists from several institutions, including the University of Illinois at Urbana-Champaign, the University of Iowa, Purdue University, Northwestern University, Pennsylvania State University, the University of Minnesota, Utah State University, the University of Tennessee, the Illinois State Water Survey, the Illinois State Geological Survey, and the U.S. Geological Survey.

Collaborative for Sediment Source Reduction (CSSR)

Several REACH PIs (Wilcock, Belmont, Gran) have initiated a science-stakeholder collaborative for developing an implementation strategy for sediment reduction in the Blue Earth watershed, which is the largest sediment source to the MRB. This work involves extrapolating our sediment budget from the Le Sueur watershed (a sub-basin of the Blue Earth watershed) and building a simulation model and decision support system with local stakeholders. This is a significant leveraging and knowledge-transfer opportunity because we will be directly collaborating with public and private decision makers in the most dynamic (amplified) portions of the watershed. This project has established a tight network of collaboration with Federal and State agencies and stakeholders to ensure that our scientific efforts take full advantage of modeling and monitoring activities in the MRB and that our results are used in informing management decisions. Additionally, the CSSR has established a stakeholder group that meets semiannually to implement a strategy for reducing fine sediment loading in the Greater Blue Earth River Basin.

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

This past year the project has resulted in training of 2 research associates, 5 post-docs, 15 graduate students, and 8 undergraduate students at the University of Minnesota Twin Cities and Duluth campuses. Post-docs being supported directly by this grant are being mentored by multiple PIs on the grant, allowing for more interdisciplinary growth and interactions. These post-docs are also given the opportunity to help mentor graduate students, write proposals and publications, and attend conferences. Post-docs and graduate students are also given the opportunity to attend our annual collaboration meetings and present their research. In 2016 our annual collaboration meeting will be held at the University of Minnesota in Minneapolis, MN. This grant is also providing training opportunities for 6 K-12 educators through our River Run initiative.

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

Results are being disseminated through presentations at scientific conferences; through meetings with stakeholders in Minnesota as part of the Collaborative for Sediment Source Reduction (CSSR), an effort by multiple REACH PIs; through the IML-CZO outreach efforts; and through educational efforts with K-12 teachers from communities within the MRB involved in the River Run project.

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

In the upcoming and final year of our WSC project, effort will be placed on synthesis and integration towards the main four objectives of the REACH project, which in short evolve around: (1) Sediment budgets: sources, pathways, and sinks of sediment and particulates; (2) Non-linear cascade of change: from climate and land-use change to hydro-ecological change; (3) Integrated nutrient and biological transport on river networks and water bodies; and (4) Conservation management strategies to promote economic development and ecological integrity.

The educational component will involve continued collaboration and support for the River Run Team educators. Curriculum development and classroom implementation will continue, with formative and summative evaluations of the curricula in the classroom, and revisions throughout the year as classroom implementations occur. Continue familiarizing participating teachers with the on-line collaborative space, facilitating development of a "Community of Practice" among the educators and students. On-going work is exploring the development of an interactive, online computer-simulation tool, grounded in process-based fundamentals elucidated by REACH project members, that allows students to explore the impact of land-management practices on nitrate levels. Additionally, we are reworking scientific articles related to the WSC scientific research into formats accessible for students and classroom use. Lastly, continue to collect and display student-created digital media related to socio-scientific issues explored within the MRB for the public.

Community and stakeholder involvement will continue, primarily through an additional stakeholder meeting run by the CSSR team. Now that our collaboration's website has been launched, this will allow for more data dissemination and knowledge transfer. The collaboration's website will be linked with the web-based GIS server to allow more easy dissemination of derived spatial datasets to stakeholders, collaborators, and the community at large.

Supporting Files

PDF Uploaded

<u>PRODUCTS</u> – What has the project produced?

Books:

Book Chapters:

Peer-Reviewed Journal Articles:

Belmont, P., J.R. Stevens, J.A. Czuba, K. Kumarasamy, S.A. Kelly (accepted), 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*.

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

Czuba, J. A., and E. Foufoula-Georgiou (2015), “Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change”, *Water Resour. Res.*, *51*, 1401–1421, doi:10.1002/ 2014WR016139.

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (in review), 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*.

Czuba, J.A., A.T. Hansen, E. Foufoula-Georgiou, and J. Finlay (in preparation), Watershed-scale nitrate removal through an interconnected complex of wetlands within a river network.

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

Dolph CL, Hansen AT & Finlay JC (accepted) Flow-related dynamics in suspended algal biomass and its contribution to suspended particulate matter in an agricultural river network of the Minnesota River Basin, USA. *Hydrobiologia*

Dolph CL, Hansen AT & Finlay JC (in review) Patterns in resource use by aquatic consumers in agricultural streams of the Minnesota River Basin, *Freshwater Biology*.

Ebtehaj, A. M., E. Foufoula-Georgiou, G. Lerman, and R. L. Bras (2015), “Compressive Earth observatory: An insight from AIRS/AMSU retrievals”, *Geophys. Res. Lett.*, *42*, 362–369, doi:10.1002/2014GL062711.

Ebtehaj, A.M., R.L. Bras, and E. Foufoula-Georgiou (2015), “Shrunken locally linear embedding for passive microwave retrieval of precipitation”, *IEEE Trans. on Geosci. and Remote Sens.*, *53*(7), 3720-3736, doi:10.1109/TGRS.2014.2382436.

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., Z. Takbiri, J.A. Czuba, and J. Schwenk (2015), “The change of nature and the nature of change in agricultural landscapes: Hydrologic regime shifts modulate ecological transitions”, *Water Resour. Res.*, *51*(8), 6649-6671, doi:10.1002/2015WR017637.

Foufoula-Georgiou, E., P. Belmont, P. Wilcock, K. Gran, J.C. Finlay, P. Kumar, J.A. Czuba, J. Schwenk, and Z. Takbiri (accepted), 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*.

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.

Gran, K.B., and J.A. Czuba (2016), Sediment pulse evolution and the role of network structure, *Geomorphology*, doi:10.1016/j.geomorph.2015.12.015. **[INVITED]**.

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.

Hansen, A.T., C.L. Dolph, E. Foufoula-Georgiou, J.C. Finlay (in review), Assessing the role of remnant wetlands in containing agricultural nitrate and their potential restoration as a future solution, *Proceedings of the National Academy of Sciences of the United States of America.*

Hansen, A.T., C.L. Dolph, J.C. Finlay (in review), The indirect effect of wetlands on downstream denitrification rates in agricultural drainage ditches, *Ecosphere*.

Karahan, E. & Roehrig, G.H. (in press). Secondary School Students' Understanding of Science and Their Socioscientific Reasoning. *Research in Science Education*. http://link.springer.com/article/10.1007/s11165-016-9527-9

Karahan, E. & Roehrig, G.H. (in review). A Case Study of a Science and a Social Studies Teachers' Experiences of Co-Teaching SSI-Based Environmental Ethics Class. *Cultural Studies of Science Education.*

Khosronejad A. , A.T. Hansen, J.L. Kozerak, K. Guentzal, M. Hondzo, P. Wilcock, M. Guala, J.C. Finlay (2016), "High fidelity LES simulation of turbulence and contaminant transport in a real-life stream: conservative tracer", Journal of Geophysical Research - Earth Surface.

Kuenzer, C., I. Klein, T. Ullmann, E. Foufoula-Georgiou, R. Baumhauer, and S. Dech (2015), "Remote Sensing of River Delta Inundation: exploiting the Potential of coarse spatial Resolution, temporally-dense MODIS Time Series", *Remote Sens.*, *7*, 8516-8542, doi:10.3390/rs70708516.

Pelletier, J.D., A.B. Murray, J.L. Pierce, P.R. Bierman, D.D. Breshears, B.T. Crosby, M. Ellis, E. Foufoula-Georgiou, A.M. Heimsath, C. Houser, N. Lancaster, M. Marani, D.J. Merritts, L.J. Moore, J.L. Pederson, M.J. Poulos, T.M. Rittenour, J.C. Rowland, P. Ruggiero, D.J. Ward, A.D. Wickert, and E.M. Yager (2015), "Forecasting the response of Earth's surface to future climatic and land-use changes: A review of methods and research needs", *Earth's Future*, *3*, doi:10.1002/2014EF000290.

Schwenk, J., S. Lanzoni, and E. Foufoula-Georgiou (2015), "The life of a meander bend: connecting shape and dynamics via analysis of a numerical model", *J. Geophys. Res. Earth Surf.*, *120*(4), 690-710, doi:10.1002/2014JF003252.

Schwenk, and E. Foufoula-Georgiou (in review), Nonlinearity of Meandering River Planforms Revisited, *Journal of Geophysical Research – Earth Surface*.

Schwenk, J., M. Fratkin, A. Khandelwal, V. Kumar, and E. Foufoula-Georgiou (in review), Resolving annual planform dynamics using Landsat imagery: the PCALM toolbox. *IEEE Transactions on Geoscience and Remote Sensing.*

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*.

Singh, A., L. Reinhardt, and E. Foufoula-Georgiou (2015), "Landscape re-organization under changing climatic forcing: results from an experimental landscape", *Water Resour. Res.*, doi:10.1002/2015WR017161.

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Tejedor, A., A. Longjas, I. Zaliapin and E. Foufoula-Georgiou (2015), "Delta channel networks: 1. A graph-theoretic approach for studying connectivity and steady-state transport on deltaic surfaces", *Water Resour. Res.*, doi: 10.1002/2014WR016577.

Tejedor, A., A. Longjas, I. Zaliapin and E. Foufoula-Georgiou (2015), "Delta channel networks: 2. Metrics of topologic and dynamic complexity for delta comparison, physical inference and vulnerability assessment", *Water Resour. Res.*, doi: 10.1002/2014WR016604.

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Tessler, Z.D., C.J. Vorosmarty, M. Grossberg, I. Gladkova, H. Aizenman, J. Syvitski, and E. Foufoula-Georgiou (2015), "Profiling risk and sustainability in coastal deltas of the world", *Science*, *349*(6248), 638-643, doi:10.1126/science.aab3574.

Thesis/Dissertations:

Czuba, J. A. (2016), A Network-Based Framework for Hydro-Geomorphic Modeling and Decision Support with Application to Space-Time Sediment Dynamics, Identifying Vulnerabilities, and Hotspots of Change, PhD. Dissertation, University of Minnesota, pp. 172.

Karahan, E. (2015), Case Studies of Secondary Science Teachers Designing Socioscientific Issues Based Instructions and Their Students' Understanding of Science and Socioscientific Reasoning, PhD. Dissertation, University of Minnesota, pp. 222.

Mitchell, N., 2015. Achieving peak flow and sediment loading reductions through increased water storage in the Le Sueur watershed, Minnesota: A modeling approach. M.S. Thesis: University of Minnesota Duluth, 126 p.

Targos, C.A., 2016. Changes in channel geometry through the Holocene in the Le Sueur River, south-central Minnesota, USA. M.S. Thesis: University of Minnesota Duluth, 90 p.

Conference Papers and Presentations:

Acosta A., A.T. Hansen (2015), Effects of Vegetation and Depth on Nitrate Reduction in Two Minnesota Wetlands, International Environmental Youth Symposium 2015: "One World, One Environment", Atlanta, Georgia, 1-2 October 2015 [**2nd place student poster in subject category**].

Andzenge, S., Koenig, W., & Loiselle, E. (April, 2016). Outdoor Classroom: Connecting Learners and Community through Environmental Science and Service Learning. Paper presentation at the annual meeting of the Green School Conference and Expo, Pittsburgh, PA.

Batts, V., Gran, K., 2015, The role of fine sediment in the morphologic evolution of vegetated, braided channel networks: Results from flume experiments. Presented at the fall American Geophysical Union meeting, Dec. 14-18, San Francisco, CA. Abstract EP51C-0932.

Charwood L. (2015) Potential Changes in Denitrification of Wetlands dominated by Invasive Typha x glauca, 11th annual First American Land Consortorium (FALCON), Denver, Colorado, November 7-9, 2015.

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (2016), Modeling bed-material sediment transport on a river network, River Flow 2016 – Eighth International Conference on Fluvial Hydraulics, St. Louis, Missouri, 12-15 July.

Czuba, J.A., E. Foufoula-Georgiou, A. Hansen, J. Finlay, K. Gran, P. Belmont, and P. Wilcock (2016), Where to manage for watershed sustainability?, Institute on the Environment Sustainability Symposium, St. Paul, Minnesota, 15 April.

Czuba, J.A., and E. Foufoula-Georgiou (2016), Guiding stream restoration from a watershed-scale perspective: A first-order approach for understanding environmental dynamics on river networks, Upper Midwest Stream Restoration Symposium, Milwaukee, Wisconsin, 7-10 February.

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (2015), Near-channel sediment sources dominate in modern agricultural landscapes: The emergence of river-network models to guide watershed management, EP24B-03, AGU Fall Meeting, San Francisco, California, 14-18 December. **[INVITED; Awarded Outstanding Student Paper Award]**

Czuba, J.A., E. Foufoula-Georgiou, A.T. Hansen, J.C. Finlay, and P.R. Wilcock (2015), A network-based approach for modeling water, sediment, and nutrient dynamics: Guiding watershed management through a systems perspective, H12C-01, AGU Fall Meeting, San Francisco, California, 14-18 December. **[INVITED]**

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (2015), Identifying hotspots of channel migration in the Minnesota River Basin, Minnesota Water Resources Conference, St. Paul, Minnesota, 13-14 October.

Danesh-Yazdi, M., E. Foufoula-Georgiou, and D. L. Karwan (2015), "Interplay of climate and land-use change on transport dynamics of intensively managed landscapes: a catchment travel time distribution analysis", H11I-1457, AGU Fall Meeting, San Francisco, California, 14-18 December.

Ebtehaj, A., E. Foufoula-Georgiou, and R. L. Bras (2015), "Rainfall Microwave Spectral Atoms: A New Class of Bayesian Algorithms for Passive Retrieval", H11O-07, AGU Fall Meeting, San Francisco, California, 14-18 December.

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

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

Foufoula-Georgiou, E., J. A. Czuba, P. Belmont, P. R. Wilcock, K. B. Gran, and P. Kumar (2015), "Climate and Humans as Amplifiers of Hydro-Ecologic Change: Science and Policy Implications for Intensively Managed Landscapes", H33O-02, AGU Fall Meeting, San Francisco, California, 14-18 December. **[INVITED]**

Foufoula-Georgiou, E., and A. Ebtehaj (2015), "Resolving Extreme Rainfall from Space: A New Class of Algorithms for Precipitation Retrieval and Data Fusion/Assimilation with Emphasis on Extremes over Complex Terrain and Coastal Areas", NH42A-02, AGU Fall Meeting, San Francisco, California, 14-18 December. **[INVITED]**

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.

Gran, K.B., Cho, S.J., Hobbs, B., Belmont, P., Wilcock, P., Kumarasamy, K., Heitkamp, B., Marr, J., February 8, 2016, Prioritization of restoration actions using real-time reduced complexity modeling in a large agricultural watershed. Talk presented at the 2016 Upper Midwest Stream Restoration Symposium, Milwaukee, WI.

Gran, K.B., January 15, 2016, Sediment source reduction at a watershed scale: Incorporating geomorphic history into watershed management. Talk given at the Minnesota Quaternary Science meeting, sponsored by the Minnesota Geological Survey.

Gran, K.B., March 3, 2016, Cleaning up the muddy Minnesota River: Incorporating geomorphic history into watershed management. Geology department seminar at the University of Illinois, Urbana-Champaign.

Gran, K.B., March 9, 2016, Targeting water storage to maintain productive land and restore clean water. Talk given to the Waseca County Farmer Forum.

Gran, K.B., December 2015, Watershed-scale prioritization for fine sediment reduction: Greater Blue Earth River Basin. Presentation given to Water Resources group at Barr Engineering.

Hansen A.T., C. Dolph, J.C. Finlay (2015) Wetlands and Lakes Reduce Surface Water Nitrogen in Minnesota's Agricultural Landscapes, Minnesota Water Resources Conference, St. Paul, Minnesota, 13-14 October.

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

Karahan, E. & Roehrig, G.H. (April, 2016). Case Studies of Secondary School Science Teachers Designing Technology Rich SSI-Based Instruction. Paper presentation at the annual regional meeting of the National Association for Research in Science Teaching, Baltimore, MD.

Longjas, A., A. Tejedor, I. Zaliapin, and E. Foufoula-Georgiou (2015), "Vulnerability maps of deltas: quantifying how network connectivity modulates upstream change to the shoreline", CSDMS Annual Meeting, Boulder, Colorado, 26-29 May.

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.

Mitchell, N., Gran, K., Cho, S.J., Dalzell, B., Kumarasamy, K., 2015, Achieving peak flow and sediment loading reductions through increased water storage in the Le Sueur watershed, Minnesota: A modeling approach. Presented at the fall American Geophysical Union meeting, Dec. 14-18, San Francisco, CA. Abstract H11K-07.

Roehrig, G.H., Andzenge, S., Karahan, E., & McFadden, J. (October, 2015). Service Learning in High School Environmental Science Classrooms. Paper presentation at the annual regional meeting of the National Science Teacher Association, Kansas City, MO.

Schwenk, J., and E. Foufoula-Georgiou (2015), "Nonlocal effects of local cutoff disturbances along the meandering Ucayali River in Peru", EP53D-05, AGU Fall Meeting, San Francisco, California, 14-18 December.

Schwenk, J., and Efi-Foufoula Georgiou (2015), "Accelerated migration rates downstream of a human-induced cutoff in the Ucayali River, Peru." 9th Symposium on River, Coastline, and Estuary Morphodynamics. Iquitos, Peru, 30 August – 3 September.

Singh, A., A. Tejedor, I. Zaliapin, L. Reinhardt, and E. Foufoula-Georgiou (2015), "Experimental evidence of dynamic re-organization of evolving landscapes under changing climatic forcing", EGU2015-8726, EGU General Assembly, Vienna, Austria, 12-17 April.

Singh, A., A. Tejedor, I. Zaliapin, L. Reinhardt, and E. Foufoula-Georgiou (2015), "Experimental evidence of reorganizing landscape under changing climatic forcing", NG23B-1786, AGU Fall Meeting, San Francisco, California, 14-18 December.

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.

Takbiri, Z., A. Ebtehaj, and E. Foufoula-Georgiou (2015), "Microwave Signatures of Inundation Area", H13H-1658, AGU Fall Meeting, San Francisco, California, 14-18 December. **[Awarded Outstanding Student Paper Award]**

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

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

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

Tejedor, A., A. Longjas, R. Caldwell, D. A. Edmonds, I. Zaliapin, and E. Foufoula-Georgiou (2015), "Moving beyond the Galloway diagrams for delta classification: Connecting morphodynamic and sediment-mechanistic properties with metrics of delta channel network topology and dynamics", GC44C-03, AGU Fall Meeting, San Francisco, California, 14-18 December.

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.

Tessler, Z.D., C.J. Vorosmarty, M. Grossberg, I. Gladkova, H. Aizenman, J. P. Syvitski, and E. Foufoula-Georgiou (2015), "The Geophysical, Anthropogenic, and Social Dimensions of Delta Risk: Estimating Contemporary and Future Risks at the Global Scale" GC44C-01, AGU Fall Meeting, San Francisco California, 14-18 December. **[INVITED]**

Websites:

(1) The River Run team has created, supported, and maintained a publicly viewable Word Press website since September 2013. The website can be found at (http://stem-projects.umn.edu/riverrun/). The website contains information that outlines the project's purpose, researcher bios, and location of participating schools and teachers. The primary use of the website thus far has been the accumulation of curriculum, resources, and data collection protocol for participating teachers. The site serves as a central hub for the dissemination of digital media to teachers and students (as well as the public) involved in the River Run. This site also contains updated information and articles pertinent to the project.

Future developments will focus on creating a digital space for student-created digital media (videos, projects, etc.) along with providing a virtual space for teachers to communicate. The goal is to give students a platform to showcase projects they've worked on in science classrooms located within the MRB while also getting participating teachers to use the website as a more central aspect of their teaching when teaching units involving the MRB. These efforts will be a major focus of interest for the research team and participating teachers/students in the upcoming year.

(2) The REACH website officially launched in August 2014. The website is hosted on the University of Minnesota STEM projects server and linked with the education and outreach webpage. (http://stem-projects.umn.edu/reach/about-the-minnesota-river-basin/)

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

A web-based GIS site has been developed for data exchange between collaborators and stakeholders. This site is currently set up only for internal data sharing, but specific files will be made public as they become available for sharing with stakeholders and the scientific community at large. Datasets that will become available include inventories and associated characteristics of erosional hot spot landforms in the Greater Blue Earth River basin; channel delineations from modern and historic aerial photographs; and spatial derivatives of high-resolution LiDAR topographic data for the MRB. These files will be made available once datasets are finalized.

<u>PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS</u> – Who has been involved?

1. What individuals have worked on the project?

Efi Foufoula-Georgiou (PI)

Jacques C Finlay (PI)

Karen B Gran (PI)

Gillian H Roehrig (PI)

Brent Dalzell (research associate)

Chris Lenhart (research associate)

Amy Hansen (post-doc)

Anthony Longjas (post-doc)

Alejandro Tejedor (post-doc)

Christy Dolph (post-doc)

Ben Janke (post-doc)

Jonathan Czuba (graduate student)

Mohammad Danesh-Yazdi (graduate student)

Jon Schwenk (graduate student)

Zeinab Takbiri (graduate student)

Evelyn Boardman (graduate student)

Sarah Winikoff (graduate student)

Anika Bratt (graduate student)

Anna Baker (graduate student)

Ian Treat (graduate student)

Rebecca Hammer-Lester (graduate student)

Nathaniel Mitchell (graduate student)

Courtney Targos (graduate student)

Virginia Batts (graduate student)

Narmin Ghalichi (graduate student)

Senenge Andzenge (graduate student)

Katie Kemmit (undergraduate student)

Erika Senyk (undergraduate student)

Andrea Keeler (undergraduate student)

Evan Lahr (undergraduate student)

Allison Acosta (undergraduate student)

LeAnn Charwood (undergraduate student)

Maria Roubert (undergraduate student)

Mulu Fratkin (undergraduate student)

2. What other organizations have been involved as partners?

Utah State University

Johns Hopkins University

University of Illinois Urbana-Champaign

Iowa State University

University of Washington

Other collaborators and stakeholder groups:

Minnesota Pollution Control Agency

St. Croix Watershed Research Station

Gustavus Adolphus College

Minnesota Department of Natural Resources

Minnesota Corn Growers Association

Minnesota Agricultural Water Resource Center

Blue Earth County

Greater Blue Earth River Basin Alliance

Minnesota Soybean Growers Association

University of Minnesota Extension Agency

Minnesota Department of Agriculture

3. Have other collaborators or contacts been involved?

Yes.

<u>IMPACT</u> – What is the impact of the project? How has it contributed?

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

The specific goal of the REACH project to understand the chain of events from precipitation to streamflow, to sediment, to stream biological activity change, and integrate this knowledge with socio-economic factors towards a science-informed decision making framework for water sustainability.

The project involves PIs that are experts in hydrology, geomorphology, river morpho-dynamics, hydro-informatics, biology, ecology, socio-economics, and education/public outreach. The work also combines field monitoring, theoretical work, and coupled hydrologic, biologic, geomorphic, and economic modeling of watersheds and their response to change geared towards informing management and policy decisions. While important discoveries are made in each of these fields (see reports of each PI for more details), it is the synthesis of these developments and the across-disciplines advances that will contribute to the integrated framework that REACH aims to develop for using the best science for management decisions in the Minnesota River Basin.

What is the impact on other disciplines?

The project is by definition interdisciplinary requiring expertise from several fields; hydrology, ecology, biology, geomorphology, engineering, river morphodynamics, socio-economic sciences, and education/public outreach. At the same time, advances made in one field are spread into other fields growing the holistic knowledge required for management of natural resources including water sustainability.

The involvement of stakeholders and state-government agencies in our project is also a unique element that promises implementation of the science to decisions that matter. Three of our REACH PIs are involved in a collaborative project that meets with stakeholders in the Greater Blue Earth River basin on a semiannual basis. This forum provides a strong venue for knowledge transfer and iterative interactions with state and local agencies responsible for managing water resources in the MRB.

What is the impact on the development of human resources?

The project funds several graduate students and post-docs (see list of participants), for whom opportunities for mentoring (co-supervised by more than one project PIs), and involvement in interdisciplinary research are greatly enhancing their ability to learn and grow as young professionals. These students and post-docs are invited in the annual project meetings to present their work.

The University of Minnesota leads an REU grant on Environmental Sustainability which hosts about 15 undergraduate students (mostly from diverse minority groups) every summer to be involved in environmental and earth surface dynamics research. The REACH annual meeting is scheduled in August to coincide with the REU group such that mentoring and interaction can take place. Several of the REU students are also given projects led by REACH PIs which involve field work and laboratory experiments, including research at the Outdoor StreamLab developed jointly by the NSF Science and Technology Center (NCED: National Center for Earth surface Dynamics) and the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota. Also, our project is synergistic with the Summer Institute on Earth surface Dynamics (SIESD), offered every summer and attracting 30 plus top graduate students and young professional from all over the world.

The REACH project also includes a teacher training and curriculum development component in environmental sciences and restoration. This year, 6 K-12 teachers continue to be part of the River Run Team that has worked to develop and integrate new curricula on socio-science issues in the MRB.

What is the impact on physical resources that form infrastructure?

Our project relies on innovative combination of theory, numerical modeling, laboratory experiments, and field work. Laboratory experiments (to test river morphodynamics, sediment/tracer dispersal in rivers, and biological response to change) are performed at the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota. SAFL is a world-renown experimental laboratory on fluid and environmental dynamics and is currently renovated by NSF funds (under the Advanced Research Infrastructure Renovation Grant). Advances in our project are leveraged and leverage advances in this laboratory which are then benefitting the national community of researchers in Earth-surface dynamics.

Our project is also leveraged by a rich dataset that has been generated by Federal and State agencies, including 1-3 m resolution lidar data covering the entire MRB (an investment in excess of $2 million); temperature, precipitation, and streamflow data; and extensive water quality and biological monitoring by the Minnesota Pollution Control Agency; multiple flow, nutrient, and sediment gages on tile drains; multiple edge of field samplers and agricultural ‘demonstration’ sites, maintained in our study area by the Minnesota Department of Agriculture; multiple gages on the mainstem Minnesota River tributaries maintained by the US Geological Survey, HSPF and GSSHA model outputs from MPCA and Army Corps of Engineers, respectively, for the entire study area.

What is the impact on institutional resources that form infrastructure?

REACH PIs initiated and established the Summer Institute on Earth Surface Dynamics (SIESD) which is offered every year and attracts 30 young investigators from around the world. REACH PIs contribute annually to the projects of the REU students at the University of Minnesota, contributing to attracting them to STEM fields.

What is the impact on information resources that form infrastructure?

The data of our project will be preserved by a collaborative agreement with SEAD, Sustainable Environment through Actionable Data, an NSF-funded DataNet project. We have begun uploading and sharing our data on the SEAD server. Through our involvement with SEAD we have suggested some changes and updates to the system that are being incorporated to help ourselves as well as future users of the system.

What is the impact on technology transfer?

In the state of Minnesota, funding for large scale watershed restoration and monitoring will be available over the next 25 years through the Clean Water Legacy Amendment of the State of Minnesota. This Constitutional Amendment assigns funds from a new sales tax ($300 million per year over the next 25 years) exclusively to actions to improve water quality in the State. *Broad scale management actions will be taken, providing the opportunity for a large- scale experiment in integrative, science-based management actions.* The understanding and models that will be developed from our project are certain to influence decisions at the management and policy levels of the State to ensure that the best science is used to restore healthy ecosystem functioning of streams in the state.

Our project has established a tight network of collaboration with Federal and State agencies and stakeholders (who provided enthusiastic support letters in the proposal development stage) to ensure that our scientific efforts take full advantage of modeling and monitoring activities in the MRB and that our results are used in informing management decisions. This transfer is strengthened through the Collaborative for Sediment Source Reduction, which has established a stakeholder group that meets semiannually to implement a strategy for reducing fine sediment loading in the Greater Blue Earth River Basin.

What is the impact on society beyond science and technology?

Several PIs (Wilcock, Belmont, Gran) have initiated a science-stakeholder collaborative for developing an implementation strategy for sediment reduction in the Blue Earth watershed, which is the largest sediment source to the MRB. This work will involve extrapolating our sediment budget from the Le Sueur watershed (a component of the Blue Earth system) and building a simulation model and decision support system with local stakeholders. This is a significant leveraging and knowledge-transfer opportunity because we will be directly collaborating with public and private decision makers in the most dynamic (amplified) portions of the watershed.

Our project has established a tight network of collaboration with Federal and State agencies and stakeholders (who provided enthusiastic support letters in the proposal development stage) to ensure that our scientific efforts take full advantage of modeling and monitoring activities in the MRB and that our results are used in informing management decisions.

CHANGES/PROBLEMS

Notifications and Request

Changes in approach and reasons for change

None

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

None

Changes that have significant impact on expenditures

None

Significant changes in use or care of human subjects

None

Significant changes in use or care of vertebrate animals

None

Significant changes in use or care of biohazards

None

NSF Water Sustainability and Climate (WSC) project EAR-1209402

REACH (REsilience under Accelerated CHange)

Year 4 Progress Report for 2015–2016

University of Minnesota

Efi Foufoula-Georgiou, Jacques Finlay, Karen Gran, Gillian Roehrig

Overarching Project Goals and Objectives

The overall goal of our Water Sustainability and Climate project (called REACH: REsilience under Accelerated CHange) is to develop a framework within which the vulnerabilities of a natural-human system can be assessed to guide decision-making towards eco-hydrologic sustainability and resilience. A unique element of the developed framework is identifying and focusing on places, times, and processes of accelerated or amplified change. One specific hypothesis to be tested is that of Human Amplified Natural Change (HANC), which states that areas of the landscape that are most susceptible to human, climatic, and other external changes are those that are undergoing the highest natural rates of change. To test the HANC hypothesis and turn it into a useful paradigm for enabling water sustainability studies, a predictive understanding of the cascade of changes and local amplifications between climatic, human, hydrologic, geomorphologic, and biologic processes are being developed to identify "hot spots" of sensitivity to change and inform mitigation activities.

The developed framework is being tested in the Minnesota River Basin (MRB) where geological history, climate variability, and intensive agriculture are affecting changes in water quantity, water quality, and ecosystem health.

The project has four main objectives:

(1) Determine the extent to which current high rates of sediment production, amplified by land-use, hydrologic, and climate changes, are affected by the underlying geology and geomorphic history of the basin, guiding a topography-based predictive framework of sediment sourcing and budgeting in a dynamic landscape.

(2) Quantify how climate and land-use driven hydrologic change, amplifies and accelerates environmental and ecological change in the basin, and how nonlinearities and amplifications can be quantified and upscaled across basins of different size.

(3) Understand the interactions of the river network physical structure and biological processes, including the role of wetlands, lakes, and riparian zones in nutrient transport and cycling, phosphorous-sediment budgeting, and food web structure towards a predictive framework in highly dynamic agricultural landscapes.

(4) Propose conservation management strategies, including sediment and nutrient reduction, to sustain ecological health and species biodiversity while promoting economic development and agricultural productivity.

University of Minnesota Research Summary

During 2015-2016, our research has been integrative along five major topical areas:

1. **Predictive framework of sediment sourcing and cycling in a coupled human-natural landscape**
    1.1. Dynamics of meandering rivers and inferring geomorphic processes from patterns
    1.2. Sediment dynamics on river networks

2. **Cascade of climate and land use/land cover change to eco-hydrologic change**
    2.1. Inferring changes in water cycle dynamics of intensively managed landscapes via the theory of time-variant travel time distributions
    2.2. Feedback between hydrologic change, riparian vegetation establishment, and floodplain dynamics
    2.3. Flow-related dynamics in suspended algal biomass and its contribution to suspended particulate matter

3. **Quantifying nutrient and phosphorus cycling in intensively managed landscapes**
    3.1. Anthropogenic and environmental controls on nutrient inputs and export
    3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics
    3.3. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes

4. **The role of wetlands and water-retention structures in environmental restoration of intensively managed landscapes**
    4.1. Modeling wetland restoration scenarios for targeted mitigation of peak flows
    4.2. Network structure nitrate removal efficiency
    4.3. Evaluation of trade-offs associated with wetland interventions

5. **Engaging and educating the public**
    5.1. Socio-scientific issues
    5.2. Curriculum development and classroom implementation

1. Predictive framework of sediment sourcing and cycling in a coupled human-natural landscape

1.1. Dynamics of meandering rivers and inferring geomorphic processes from patterns

J. Schwenk and E. Foufoula-Georgiou

Meandering river planform evolution is driven by the interaction of local nonlinear hydro-morphodynamic processes and by threshold-type nonlinear dynamics via cutoffs. *Are these dynamic nonlinearities somehow encoded in the static meander planform geometries to allow inferring geomorphic process from observed static patterns?* Previous attempts have found at most a weak signature of these dynamic nonlinearities in static meander planform morphologies. Using powerful analysis and detection methodologies, our work has unambiguously showed that the spatial structure of meandering centerlines does indeed encode dynamic nonlinearities (see Fig. 1). We demonstrated this finding both in numerically simulated meandering rivers and in three natural rivers. Cutoffs were found to obscure the imprint of the dynamic nonlinearities of the governing morphodynamic processes, but they were also shown to act as a succinct source of nonlinearity themselves. The degree of nonlinearity (DNL) was measured for two meandering rivers in the Minnesota River Basin. Both the Watonwan and Blue Earth Rivers saw an overall decline in DNL from 1938 to 2008, reflecting a shift in the driving dynamics (i.e. climate and land use changes), direct channel modifications such as channel straightening, and the occurrence of 36 cutoffs over the time period (Schwenk et al., 2016a).

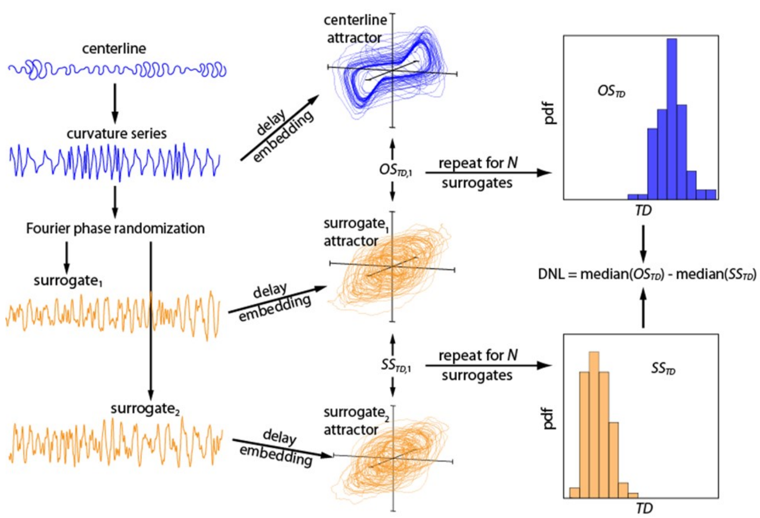

Figure 1. The procedure for computing the degree of nonlinearity (DNL) is shown. First, the curvature series is computed from a centerline. *N* surrogates of the curvature series are generated (only two are shown) by randomizing their Fourier phases. The curvature series and its surrogate are embedded in phase space and the difference between attractors ($OS_{TD,1}$) is measured with the transportation distance (TD). This procedure is repeated *N* times, resulting in the OS_{TD} distribution. The same procedure is used to generate the SS_{TD} distribution except that surrogate-surrogate pairs are compared in the embedding space. The DNL is then estimated as the distance between the medians of the SS_{TD} and OS_{TD} distributions.

Quantifying planform changes of large and actively migrating rivers is essential for advancing river morphodynamic theory, identifying controls on migration, and understanding the roles of climatic and human influences on planform adjustments. *However, efficiently extracting meandering river planform changes over large spatial domains and with high enough temporal resolution from satellite images, which are now available over the globe, presents serious challenges.* Our work addressed these challenges using Landsat imagery and introduced a set of innovate and efficient methods to map and measure spatial and temporal planform changes including local and average widths, centerline migrated areas and rates, erosion and accretion, and cutoffs (Schwenk et al., 2016b). The methods have been assembled in a comprehensive toolbox called Planform Change AnaLysis using Matlab (PCALM). As a proof-of-concept, the PCALM toolbox was applied to over 1,300 km of the actively-migrating and predominately meandering Ucayali River in Peru (see Fig. 2). Landsat 5 and 7 images collected from 1985-2015 were classified with a supervised classifier, and annual composite images were created that are shown to resolve bankfull channel and bar morphologies. Hydraulically-connected and single-thread channel masks obtained from the composite images were then used to quantify planform changes in river width, migration rates, and accretion/erosion rates and map and measure 57 cutoffs throughout the reach. The uncertainty of the analysis was estimated by quantifying planform changes for three abandoned, pseudo-stationary bends. This work opens the door for large-scale analysis of meandering rivers around the world to understand cause and effect in morphodynamic change of landscapes and provide estimates of sediment dynamics.

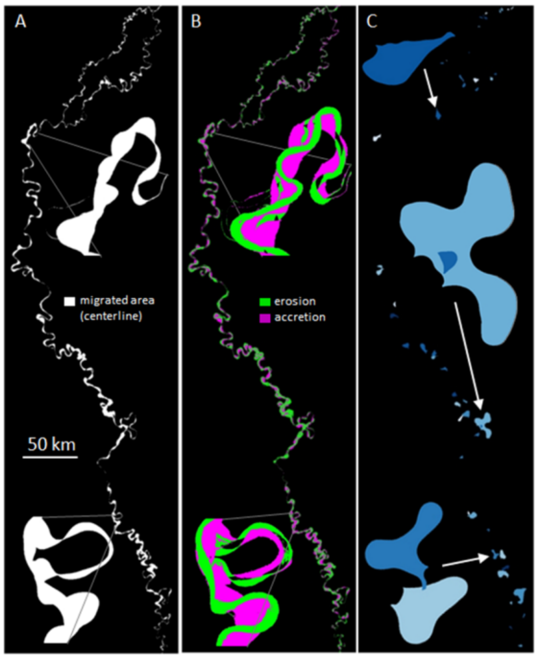

Figure 2. Migrated areas and cutoffs for the Ucayali River from 1985-2015 are computed using the developed toolbox PCALM (Planform Change AnaLysis using Matlab). Centerline migrated areas are shown in (A) with two zoom views. The scale bar refers to the entire image. Erosion and accretion maps are shown in (B) along with the same zoom views. A pixel may undergo multiple instances of erosion and/or accretion; only the latest occurrence is shown. The 57 cutoff that occurred from 1985-2015 are shown in (C). Lighter cutoff areas occurred nearer 1985, while darker occurred nearer 2015. The largest cutoff within the study reach is shown (triple-lobed) in a zoom view, as well as the third and fourth largest (pair of double-lobed).

1.2. Sediment dynamics on river networks

J. Czuba, E. Foufoula-Georgiou, K. Gran, P. Belmont (REACH PI at Utah State University), and P. Wilcock (REACH PI at Utah State University)

High-resolution topography provides a basis for accurately mapping sediment sources, identifying pathways by which sediment moves through a watershed, and quantifying the physiographic characteristics of river channels and floodplains. *We take advantage of this information for quantifying sediment dynamics not only within a river reach but within an entire watershed.* Our work developed a network-based model for bed-material sediment that combines spatially-explicit sediment sourcing with in-channel transport and storage dynamics on a river network (Czuba et al., 2016a). The model was used to simulate the transport and storage of bed-material sand over a 600-year time period in the Greater Blue Earth River Basin in Minnesota (see Fig. 3). We showed how to compute analytically the time-averaged (mean) bed-sediment thickness for each link of an entire river network for any spatial distribution of inputs. Under supply-limited conditions (sediment-transport capacity greater than sediment supply), we showed how to compute analytically the time-averaged pdf of bed-sediment thickness. Under transport-limited conditions (sediment supply greater than sediment-transport capacity), (1) the time-averaged pdf of bed-sediment thickness was heavy tailed where the magnitude of fluctuations depended on the strength of the feedback between the volume of sediment placed in storage and the resulting slope and (2) the time series of bed-sediment thickness was periodic with dominant period inversely proportional to the volumetric flux, which sets the timescale for the bed to adjust. The time series of bed-sediment thickness was the result of dynamics on a network in propagating, altering, and amalgamating sediment inputs in sometimes unexpected ways.

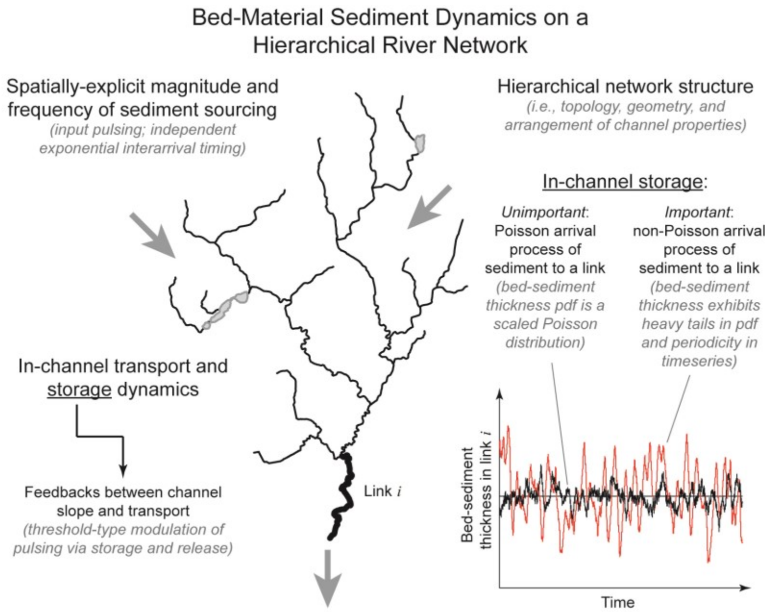

Figure 3. Conceptual overview of bed-material sediment dynamics on a hierarchical river network. The combination of spatially-explicit magnitude and frequency of sediment sourcing, hierarchal network structure, and in-channel transport and storage dynamics creates a temporal variability in bed-sediment thickness. When in-channel storage is unimportant, the probability distribution function (pdf) of bed-sediment thickness is a scaled Poisson distribution, which is directly related to the structure of the inputs. When in-channel storage is important, we see the emergence of heavy tails in the pdf and periodicity in the time series of bed-sediment thickness.

Punctuated sediment pulses are triggered in a watershed through a variety of mechanisms, from landslides to land-use change. *How do these sediment pulses move through the fluvial system and where do they create hotspots of change?* Many studies have addressed reach-scale dynamics of sediment pulses and how they translate or disperse downstream. At the watershed scale however, network structure and storage become more important in modulating the sediment signal. In this work we reviewed the current literature on sediment pulse behavior, and then addressed the role of network structure on maintaining, dispersing, or transforming sediment pulses in a fluvial system (Gran and Czuba, 2016). We used a reduced-complexity network routing model that simulates the movement of bed material through a river basin. This model was run in the Greater Blue Earth River (GBER) basin in Minnesota, USA, first with spatially uniform inputs and then with inputs constrained by a detailed sediment budget. Once the system reached equilibrium, a sediment pulse was introduced, first at a single location and then throughout the system, and was tracked as it evolved downstream. Results indicate that pulses able to translate downstream disperse in place upon arriving at over-capacity reaches as sediment goes into storage. In the GBER basin, these zones occur just upstream of a knickpoint that is propagating upstream through all mainstem channels. As the pulses get caught in these sediment "bottlenecks," there is a decoupling of the original pulse of sediment and the resulting bed material wave (see Fig. 4). *These results show that the network structure, both in terms of network geometry and the spatial pattern of transport capacity, can play a dominant role in sediment connectivity and should be considered in predictive modeling of sediment pulse behavior at the watershed scale.*

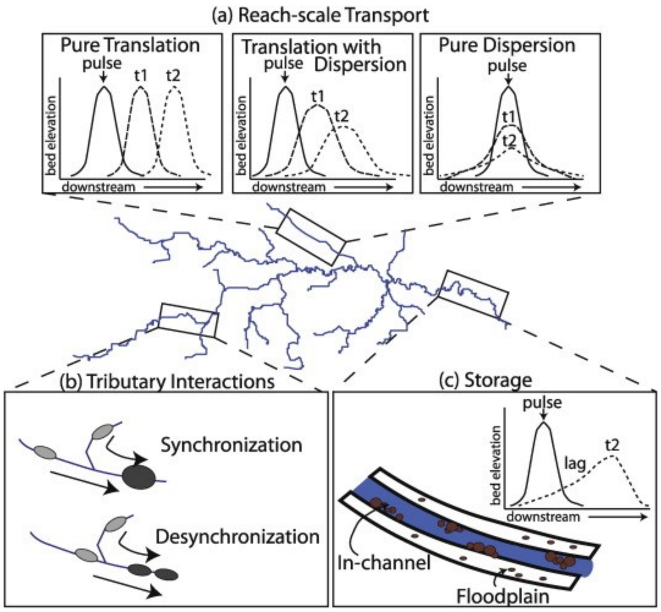

Figure 4. Conceptual figure showing potential influences on sediment pulse movement in a watershed including (a) reach-scale dynamics that lead to either dispersion, translation, or a combination of both; (b) tributary interactions that can both synchronize or desynchronize sediment waves moving downstream, and (c) in-channel and floodplain storage that leads to a lag in the sediment wave movement downstream.

2. Cascade of climate and land use/land cover change to eco-hydrologic change

2.1. Inferring changes in water cycle dynamics of intensively managed landscapes via the theory of time-variant travel time distributions

M. Danesh-Yazdi and E. Foufoula-Georgiou

Climatic trends and anthropogenic changes in land cover and land use are impacting in complex ways the hydrology and water quality of streams at the field, watershed, and regional scales. In the Midwestern U.S., the replacement of hay and small grains with row crops of corn and soybean since the 1970's has been accompanied by expansion of artificial surface and subsurface drainage, and also conversion of forests and wetlands to agricultural lands. In addition to human-induced landscape alterations, climatic trends in the Midwest have also been documented, especially following the mid-1970s with warmer temperatures, earlier snowmelt, increased annual precipitation, and rainfall events of higher intensity and shorter duration. Acknowledging that both climatic trends and human actions modulate hydrologic change, their hydro-ecological consequences are still debated in view of the observed enhanced rates of nitrate, phosphorus, and pesticides in many streams, as well as altered runoff volumes and timing. *The question we posed is whether we can infer from observed hydrologic data, changes in the storage-release dynamics of the watershed system that would explain or reveal changes in its hydrologic functionality.* In this study, we employed a lumped, stochastic Lagrangian formulation of transport within the storage selection function framework (Danesh-Yazdi et al., 2016) attempting to infer the probabilistic structure of time-variant travel time distributions with minimal assumptions and relying heavily on the available hydrologic data measured at the watershed scale. The promise of this approach lies on its potential to incorporate the influence of factors that can significantly impact the travel time distributions, such as the land-use/land-cover change considered here. *Our results from analysis of a sub-basin in the Minnesota River Basin indicate a significant decrease in the mean travel time of water in the shallow subsurface layer during the growing season under current conditions compared to the pre-1970's conditions. We also find highly damped year-to-year fluctuations in the mean travel time, indicating that the filtering of the natural heterogeneity via the artificially re-wired landscape results in a homogenization of the hydrologic response (see Fig. 5).*

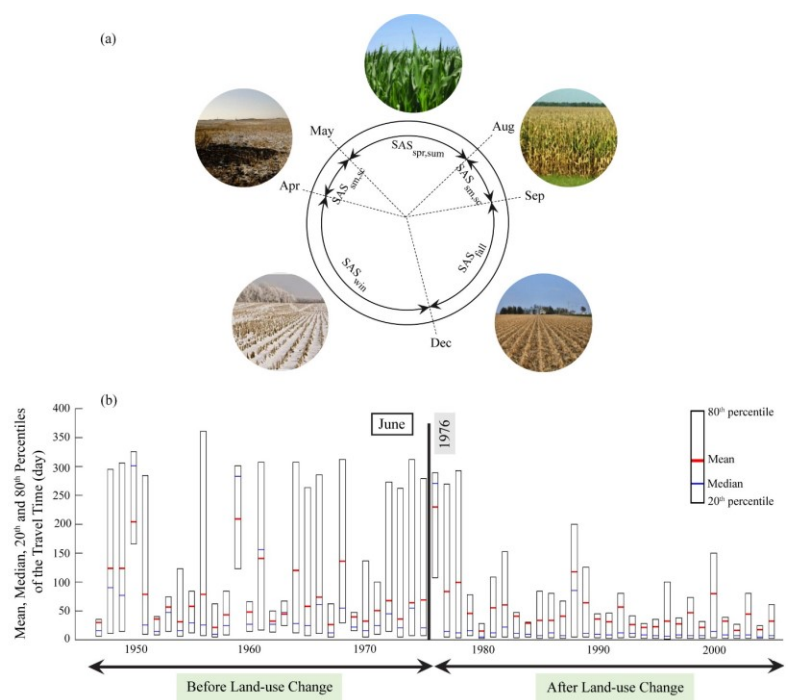

Figure 5. (a) Qualitative inference of the type of the StorAge Selection (SAS) functions for the winter (SAS_{win}), snowmelt and senescence ($SAS_{sm,sc}$), spring and summer ($SAS_{spr,sum}$), and fall (SAS_{fall}) periods. SAS functions giving higher preference to mobilizing water of older ages, younger ages, and no preference to ages are assumed for the winter, spring and summer, and snowmelt and senescence and fall periods, respectively. (b) Temporal evolution of the mean, median, 20^{th} and 80^{th} percentiles of the travel time in the month of June. Smaller distance between the mean, and 20^{th} and 80^{th} percentiles of the travel time in the after land-use change period reveals significantly reduced variability in the travel times around the mean.

2.2. Feedback between hydrologic change, riparian vegetation establishment, and floodplain dynamics

V. Batts, K. Gran, and C. Lenhart

Previous REACH research investigating historic changes in flows on the Minnesota River *found that point bars are remaining submerged for greater amounts of time during the recruitment window of dominant riparian species.* Over time, this shift can lead to more open point bars with less riparian vegetation established which may have important implications on point bar dynamics, including changes in the trapping efficiency for suspended sediment. *These observations and potential implications motivated a series of experiments to investigate the interplay between riparian vegetation, suspended sediment, and floodplain dynamics.*

Coupled experiments were conducted in a 1.5 x 5 m flume at the University of Minnesota, Duluth to observe how floodplains respond to vegetation colonization with and without suspended sediment present. In each experiment, we imposed a two-stage hydrograph, with floods lasting for four hours, followed by 6 days of low flow in which the flume was seeded with vegetation (*Medicago sativa*; see Fig. 6). Experiments lasted for up to 9 cycles of flood followed by growth. One experiment used only bedload, while the second had a mix of bedload and suspended load. Results mirror those from previous experiments in documenting the role of vegetation in corralling the flow into fewer, narrower, deeper channels and slowing channel migration rates. *Initial results indicate that suspended sediment allows the floodplain to adjust to changes in transport capacity associated with the growth and encroachment of riparian vegetation.*

Figure 6. Overbank deposition of fine sediment within a patch of vegetation (alfalfa, *Medicago sativa*).

2.3. Flow-related dynamics in suspended algal biomass and its contribution to suspended particulate matter

C. Dolph, A. Hansen, and J. Finlay

Factors controlling phytoplankton dynamics in flowing waters (lotic systems) remain poorly understood relative to those in standing waters (lentic systems), especially in smaller and mid-size streams. Here, we evaluated relationships between stream flow, suspended algal biomass and particulate organic carbon over multiple years for a mid-size river network draining an intensively managed agricultural landscape in the Midwestern USA (the Le Sueur River watershed; Dolph et al., 2016). As expected, we found that mid-size reaches (4^{th}-6^{th} order) yielded higher chlorophyll concentrations than smaller reaches (1^{st}-3^{rd} order); however, all reach types exhibited chlorophyll concentrations that could be considered eutrophic (Fig. 7). Suspended algae accounted for approximately 20% of total suspended carbon in the river network, on average. Over time, the highest levels of suspended algal biomass across all sites were associated with intermediate-high flow conditions (above median discharge but below ~25% exceedance probabilities). Lakes and wetlands were also sources of suspended algal biomass to the stream network, although substantial phytoplankton production appeared to occur in-channel independent of inputs from connected lentic systems. *Our findings highlight the importance of flow as a regulator of suspended algal biomass, and suggest that moderate flow events act to mobilize algae from benthic habitats or other refugia.* The implications of these findings for the comprehensive stream ecology within intensively managed watersheds, where changes in the magnitude-frequency of flows are observed, need to be further evaluated.

In 2016, we are collaborating with Paula Furey from St. Catherine's University, as well as Anne Wilkinson, a graduate student in the Department of Civil Engineering at the University of Minnesota, to understand how lake inputs to the river network can affect the abundance and identity of phytoplankton communities (including toxic cyanobacteria) in streams and rivers of the Le Sueur River watershed. Further research will also consider the role of algal transport in watershed phosphorus and nitrogen cycles.

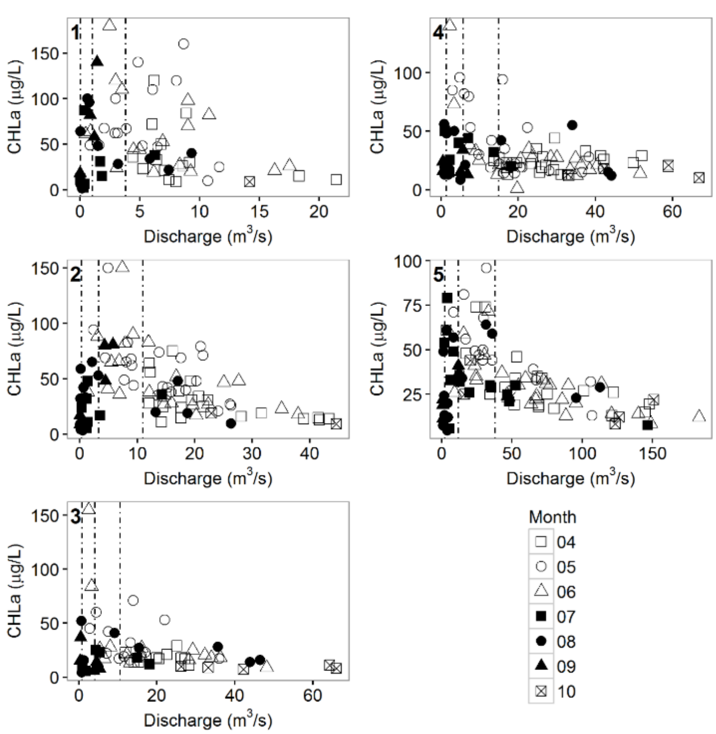

Figure 7. Chlorophyll-a (Chla) concentration in relation to mean daily discharge at five gage stations in the Le Sueur River basin. Shape indicates month in which samples were collected. Vertical dashed lines indicate discharges associated with the 75%, 50% and 25% exceedance probabilities (from left to right on each plot). Chla and discharge measurements were collected during Apr 1^{st} – Nov 1^{st} over multiple years: 1) Little Cobb River near Beauford (2005-2008); 2) Big Cobb River near Beauford (2006-2008); 3) Le Sueur River near St. Clair (2007-2011); 4) Le Sueur River near Rapidan, CR8 (2006-2008); 5) Le Sueur River near Rapidan MN 66 (representing the basin outlet; 2005-2008).

3. Quantifying nutrient and phosphorus cycling in intensively managed landscapes

3.1. Anthropogenic and environmental controls on nutrient inputs and export

E. Boardman, J. Finlay, M. Danesh-Yazdi, and E. Foufoula-Georgiou

We are exploring environmental controls and sources of watershed nitrogen (N) and phosphorus (P) losses across agricultural regions of Minnesota. We estimated Net Anthropogenic N and P Inputs (NANI and NAPI) for 62 watersheds based on modification of existing methods. Our approach takes into account atmospheric deposition, inorganic fertilizer inputs, and net food and feed inputs (including manure, crop N fixation, animal requirements, and human requirements). We considered watersheds larger than 150 km^2 due to the resolution of the input data, which is generally at the county-level. We are continuing to refine and validate our approach, including integrating data for permitted point source discharges for the study watersheds. *Our results indicate that N and P fertilizer inputs are the largest contributors to nutrient losses in agricultural watersheds* (see Fig. 8). Responses are often nonlinear and may be modified by a legacy of fertilization, inputs from permitted discharges, and landscape features such as wetlands.

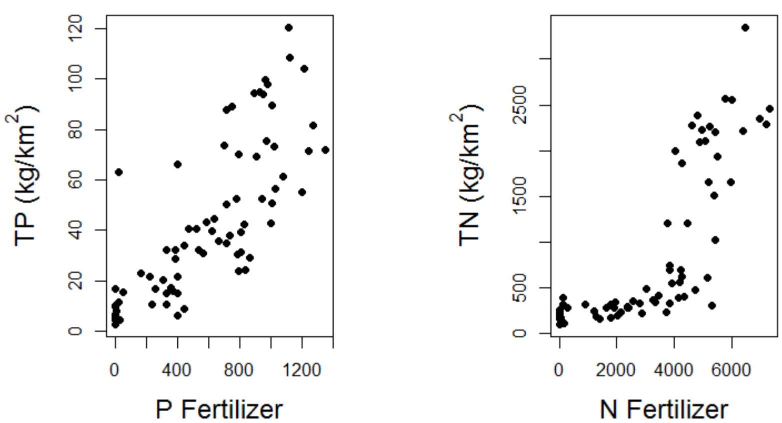

Figure 8. Total N and P export for 62 watersheds larger than 150 km^2 across a range of N and P fertilizer inputs. The outlier in the left-hand plot where P fertilizer input is near zero but TP is elevated is the Nemadji River, an anomalous watershed in NE Minnesota underlain by lake bed sediments.

We are examining hydrologic controls on N and P export in support of efforts to tie together our knowledge of the hydrology, sediment transport, geomorphology, and nutrients in agricultural watersheds. We have assembled MPCA monitoring data over 100 sites with greater than 50% agricultural land cover, as well as some sites with low and moderate agricultural land cover. By establishing concentration-discharge relationships at these sites we are examining the role of hydrology in determining nitrate and P concentrations. Notable findings thus far include the prevalence of concentrating relationships across most watersheds and the observation that flow sensitivity varies amongst watersheds (Figs. 9 and 10 top). *This suggests flow reduction BMPs may be more effective in watersheds where nutrient concentrations are more closely related to discharge.*

Our next steps include relating the concentration discharge relationships to environmental variables including slope, land cover, nutrient inputs, and permitted discharges. For instance, we have observed diluting relationships downstream of wastewater treatment plants and lake outlets (Fig. 10 bottom). We are currently obtaining more geomorphic variables for these sites and we hope to explain some of the variation in export with the relative influences of slope and features such as bluffs and ravines.

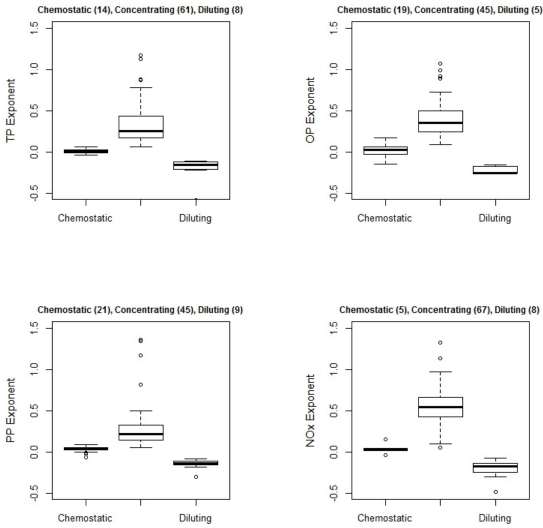

Figure 9. Exponents of power law relationships between constituent concentrations and discharge in highly agricultural watersheds monitored by the MPCA. An exponent of 0 denotes no relationship while a positive exponent of 0.5-0.6 denotes a strong nonlinear dependence, highlighting the hydrologic control on nutrient exports.

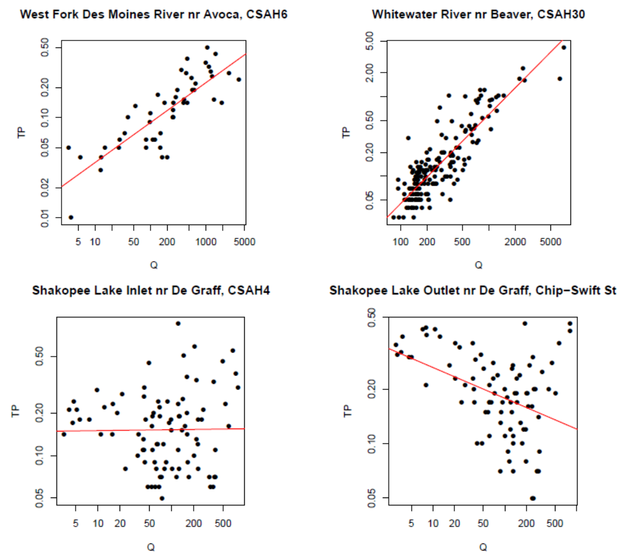

Figure 10. Concentration discharge relationships for total phosphorus showing (top) different slopes in TP increases across a similar range of discharges and (bottom) a lake inlet-outlet pairing that switches from a chemostatic to diluting relationship along its continuum. Some of the highest concentrating exponents have been observed in southeastern Minnesota, suggesting geological or other environmental factors affect these relationships.

3.2. The role of sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics

A. Baker, J. Finlay, and K. Gran

New integrative research is being undertaken to examine the role of interactions between phosphorus and sediment in driving watershed-scale phosphorus dynamics in the Greater Blue Earth River Basin. *We are exploring phosphorus export and retention as a function of sediment geochemistry and sorptive capacity across a geomorphic gradient via the development of a phosphorus budget and experimental in-channel sediment incubations.* The phosphorus budget will be tightly coupled to the sediment budget previously developed by project PIs (K. Gran, P. Belmont (Utah State University), and P Wilcock (Utah State University)). This sediment budget identifies bluff, stream bank, ravine, and agricultural field erosion as dominant sources of sediment to the Greater Blue Earth Basin. In order to understand how these distinct sources contribute to watershed phosphorus loads, sediment is being collected across the basin representing variability in phosphorus content, texture, and phosphorus sorptive capacity of the individual sediment sources described by the budget. Data describing total, available, and dissolved phosphorus associated with these sediments will be applied to the sediment budget to estimate the contributions of sediment to water column P loads. These estimates will be compared to loads measured by the Minnesota Pollution Control Agency at monitoring gages.

The mass balance provided by the phosphorus budget will be refined via experimentation in the form of in-channel sediment incubations. Incubations will involve the installation of sediment from distinct sources across the fluvial network at points along a geomorphic gradient and subsequent monitoring of changes in sediment phosphorus content. These data will be used to develop functional relationships describing interactions between phosphorus and sediment derived from unique erosional sources in the basin. These functional relationships can then be applied to existing models for sediment routing created by the REACH group, improving our ability to target management for the reduction of both sediment and phosphorus.

3.3. Quantifying the capacity of remnant wetlands to remove nitrate from agricultural landscapes

A. Hansen, C. Dolph, E. Foufoula-Georgiou, and J. Finlay

Increased reactive nitrogen input, primarily to support industrial scale agriculture, is arguably the single largest change that humans have made to global biogeochemistry. Intensively managed agriculture provides an attractive economy of scales that supports the growing global population size and increasing affluence while minimizing the areal footprint of agriculture. For example, in many parts of the Midwestern USA, 40 – 95 % of the land is dedicated to row-crop agriculture, primarily corn and soy production (Fig. 11a). Wetland cover has been greatly reduced in this landscape, due to drainage during the conversion from a prairie-wetland mosaic to farmland. Current wetland cover within the Upper Mississippi River basin and Ohio River Basin is 1-10% which is on average a 60% reduction from historic coverage for the region and up to 95% loss for Iowa, for example (Fig. 11b). *Reductions in wetland cover combined with increased N inputs via fertilizer have led to a sustained rise in nitrate (NO_3^-) concentrations in surface and groundwater throughout much of the region.*

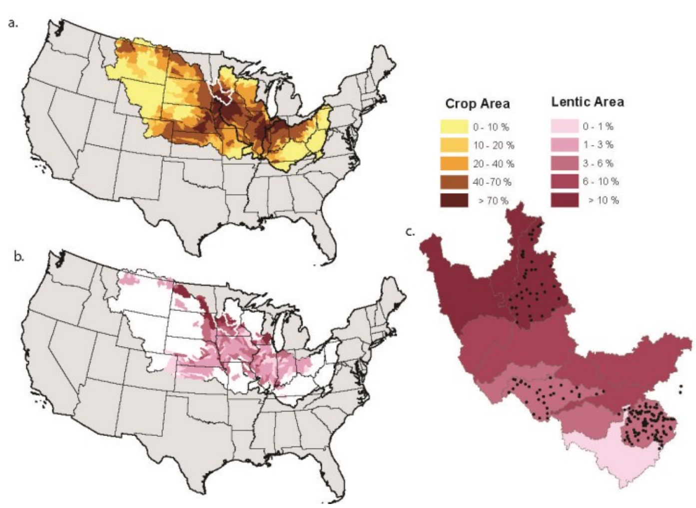

Figure 11. Maps of land use most relevant to nitrate loading within northern Mississippi River Basin (Missouri, Ohio, and Upper Mississippi River basins). a.) Percent row crop agriculture. Shading applied based on HUC 8 sub-basin averages. b.) Percent lentic (wetlands + lakes) cover for HUC 8 sub-basins with greater than 40% row crop agriculture. Non-shaded basins have less than 40% row crop agriculture. Minnesota River Basin is outlined in white. c.) Map of all sites sampled for this analysis (black circles). 180 total locations within the Minnesota River Basin were sampled during June and August, 2013 – 2015. Sites were sampled between 1 to 6 times. Sites were chosen to span a large range in drainage areas (0.253 km^2 to 5,239 km^2) and in in land use (% crop land cover between 30% - 95%, % lentic cover between 0.0 to 58%).

Numerous studies have demonstrated that individual wetlands and lakes are effective at removing nitrogen at an annual and event scale. Effectiveness for nitrate removal is primarily dependent on residence time and inlet NO_3^- concentrations. However, natural remnant wetlands may not be effective at decreasing nitrate due to their landscape position, size, degraded condition, and extremely high NO_3^- loading rates. *With a three year, multi-basin field study we tested the hypothesis that wetlands and lake cover was predictive of NO_3^- concentrations within an intensively managed, row crop agricultural landscape.* We found that June NO_3^- concentrations within a fluvial network decreased exponentially with the percent of land use by lentic systems within the contributing drainage area. This result was independent of the size of the contributing drainage area across a range of 1 to 6,000 km^2. Nitrate was most strongly related to the percent of saturated wetlands with emergent vegetation although lakes also had a discernible effect. We demonstrate that unlike grasslands, which behave simply as the absence of crop land, the effect of wetlands and lakes on NO_3^- was due to both the absence of cropland and to a positive effect of wetlands on nitrate removal. NO_3^- concentrations are estimated to currently be triple what they would be if agricultural land conversion has not included draining historic wetlands. Conversely, this result demonstrates that wetland restoration would be highly effective at reducing NO3 in the context of intensively managed agriculture (Hansen et al., 2016a).

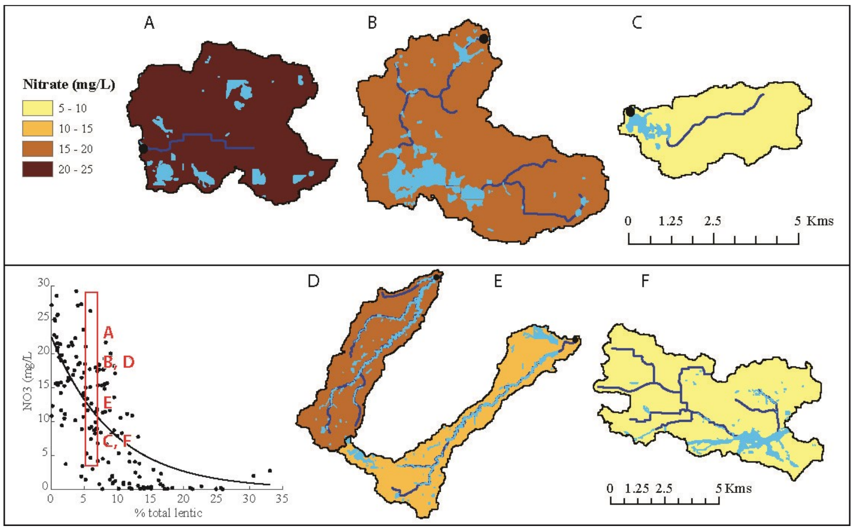

Figure 12. Location of wetlands and their connectivity to the river network matters in terms of controlling nitrate concentration downstream. June nitrate concentrations decreased exponentially with percent wetland and lake land cover ($NO_3^- = 22.4e^{-0.107(\%lentic)}$, $R^2 = 0.51$, $n = 165$). Percent total lentic cover, the predictive variable, does not consider many factors that could influence the effectiveness of wetlands at reducing basin scale nitrate. For example, isolated wetlands will not intercept much of the water (A), riverine floodplains as in (D, E) do receive water from the entire drainage area but have low residence time, wetlands located upstream of inputs will not intercept these and how lower effect on output (B). NO_3^- in A – C were observed in 2015 and NO_3^- in D – F were observed in 2014.

Wetlands are known to be effective sinks for nitrate. Wetland restoration and construction have gained traction as viable conservation measures to improve water quality in intensively managed agricultural landscapes. In addition to reducing nitrate in situ, wetlands may have impacts on water quality and temperature dynamics that extend beyond the confines of the wetlands themselves. Non-saturating nitrate concentrations enhanced organic carbon effluxes and altered temperature dynamics could all potentially enhance denitrification rates within a stream network, thus extending water quality benefits beyond the wetland boundary. *We investigated the effect of wetlands on water chemistry, water temperature and benthic denitrification rates in downstream agricultural ditches through a field measurement campaign over the open water season.* We found that, although ditches located downstream of wetlands had lower NO_3^- and higher DOC, ditch denitrification rate was not significantly altered by the presence of upstream wetlands. Rather, wetlands indirectly effected denitrification within ditches by strongly influencing the stoichiometry of the two limiting resources, NO_3^- and organic carbon. Peak denitrification rates were observed when DOC and NO_3^- supplies were approximately balanced i.e. at DOC: NO_3^- ratios that were near the microbial requirement for denitrification. NO_3^- limitation occurred primarily at sites with > 3.5% wetland cover, and in the fall at all sites, and DOC limitation occurred primarily at sites with < 1% wetland cover (Hansen et al., 2016b). Temperature was found to be a secondary control, only important when NO_3^- and DOC resources were balanced. *Our results suggest that wetland restoration and construction targeting nitrate reduction within intensively* *agriculturally managed basins should be implemented in a way that promotes balanced resource availability throughout fluvial networks. Wetlands are an important regulator of resource availability and thus could be used to create conditions that maximize denitrification in NO_3^- enriched watersheds.*

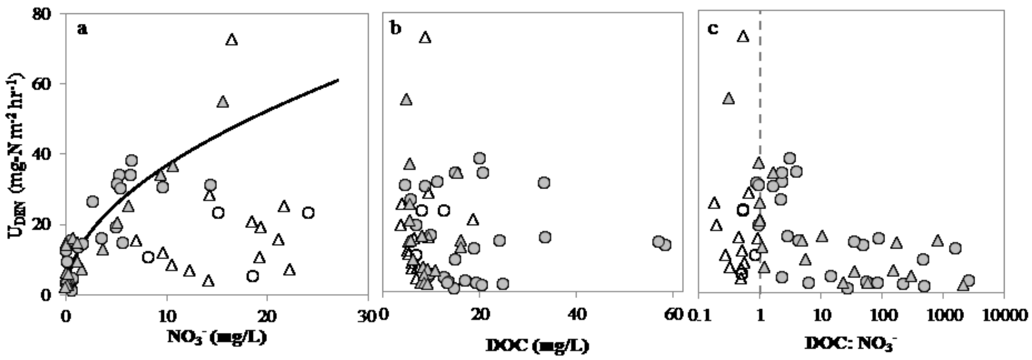

Figure 13. Denitrification rate (U_{DEN}) was determined to be limited by either NO_3^- or DOC. Observations from sites with high wetland influence are shown with circles and from sites with minimal wetland influence are shown with triangles. In panel a, samples that fit a NO_3^- limitation model are shown in gray and all other samples are hollow symbols. The upper limit on U_{DEN} was constrained by NO_3^- availability and could be modeled using a previously published model of denitrification by Mulholland et al. 2008 and extended by Bohlke et al. 2009 (solid line, panel a). Grey symbols are observations that are well described by the NO_3^- limitation model and open symbols are the observations not well described by the model. We did not find a predictive relationship between U_{DEN} and DOC (panel b) although when U_{DEN} was plotted against the ratio of DOC: NO_3^- data that did not fit the NO_3^- limited model was found to group together and have DOC: $NO_3^- < 1$, likely indicating insufficient organic carbon (panel c).

4. The role of wetlands and water-retention structures in environmental restoration of intensively managed landscapes

4.1. Modeling wetland restoration scenarios for targeted mitigation of peak flows

N. Mitchell, K. Kumarasamy, and K. Gran – Le Sueur River

B. Dalzell and C. Kling (REACH PI at Iowa State University) – Cottonwood River

In the Minnesota River Basin, sediments originating from eroding stream banks and bluffs account for the majority of the riverine load and contribute to water quality impairments in the Minnesota River as well as portions of the Mississippi River upstream of Lake Pepin. One approach for mitigating this problem may be targeted wetland restoration in Minnesota River Basin tributaries in order to reduce the magnitude and duration of peak flow events which contribute to bluff and stream bank failures. In order to determine effective arrangements and properties of wetlands to achieve peak flow reduction, we worked in two tributaries of the Minnesota River, the Cottonwood, and the Le Sueur. The Le Sueur River assessment investigated the placement and properties of wetlands in a SWAT modelling framework, from which a reduced complexity model was developed to provide rapid results for use in a stakeholder group. The Cottonwood River employed a genetic algorithm coupled with a SWAT watershed simulation model to assess the most cost-effective placement of wetlands to achieve peak flow reduction.

In the Le Sueur basin, potential wetland sites were identified from lidar data as topographic depressions with high compound topographic index values. Wetland parameters including surface area, volume, and hydraulic conductivity of basal sediments were varied in three distinct zones within the watershed. *Results from the Le Sueur indicate that the effectiveness of wetlands at reducing peak flows is strongly related to the hydraulic conductivity of the wetland sites, which affects the residence time of water in the wetland features, with higher hydraulic conductivity or lower residence times providing the biggest reduction in peak flows* (Fig. 14). Reductions in peak flow were directly translated into reductions in sediment loading from bluff and bank erosion via a relationship developed by Se Jong Cho (working with REACH PI P. Wilcock) from paired gage data. Reductions in peak flow and sediment loading were most effective when wetlands with high hydraulic conductivity were placed high in the watershed, far from the mouth. This contrasts with results from the Cottonwood discussed below. The results from the Le Sueur were used in the development of a management options simulation model (MOSM) designed to be used with stakeholder groups in the watershed to develop a portfolio of management options to reduce sediment loading in the Greater Blue Earth River basin (as part of the Collaborative for Sediment Source Reduction project, collectively sponsored by Federal and State agencies and local stakeholder groups).

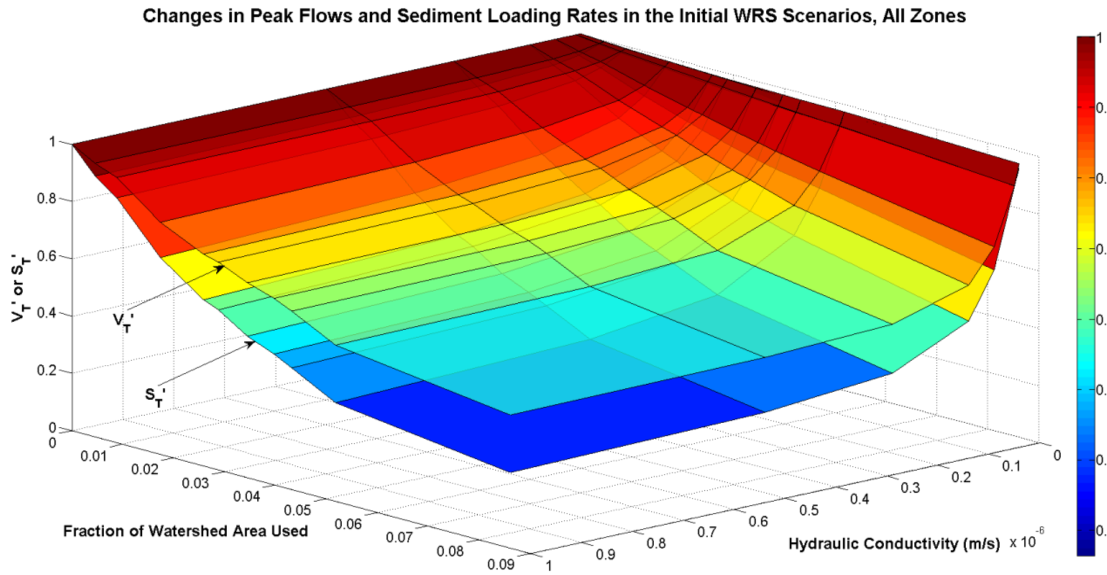

Figure 14. Results from the Le Sueur watershed showing the reduction in peak flow (V_T') and sediment loading (S_T') above the threshold where near-channel erosion from banks and bluffs increased rapidly. The threshold value was determined through paired gage analyses. The results here show an increase in effectiveness with increasing area of wetland installed and increasing hydraulic conductivity of underlying sediments.

The genetic algorithm approach is capable of evaluating combinations of basic wetland features as represented by SWAT: surface area, volume, contributing area, and hydraulic conductivity of the wetland bottom. These wetland parameters were weighed against economic considerations associated with land use trade-offs in this agriculturally productive landscape. Results show that the SWAT model is capable of simulating daily hydrology very well and increasing extent of wetland restoration is capable of reducing the number of days that watershed peak flows are above threshold values associated with most sediment export. *More specifically, the genetic algorithm approach showed that wetland restoration nearest the watershed outlet and along the main downstream portions of the Cottonwood River generated the greatest reduction in peak flow days for the least cost. Increasing scenarios of peak flow reduction were achieved by more widespread adoption of wetland restoration throughout the watershed* (Fig. 15). Additional analysis of these outcomes, however, reveal that key rainfall events may play a role in how wetland restoration scenarios are selected due to intense but spatially isolated thunderstorms. Ongoing efforts to implement a genetic algorithm approach for wetland restoration scenarios will focus on running the model with an idealized set of rainfall inputs, which will permit more explicit determination of the role that watershed characteristics (e.g., shape, size, topography, soils) can play in the spatial arrangement of wetland restoration scenarios.

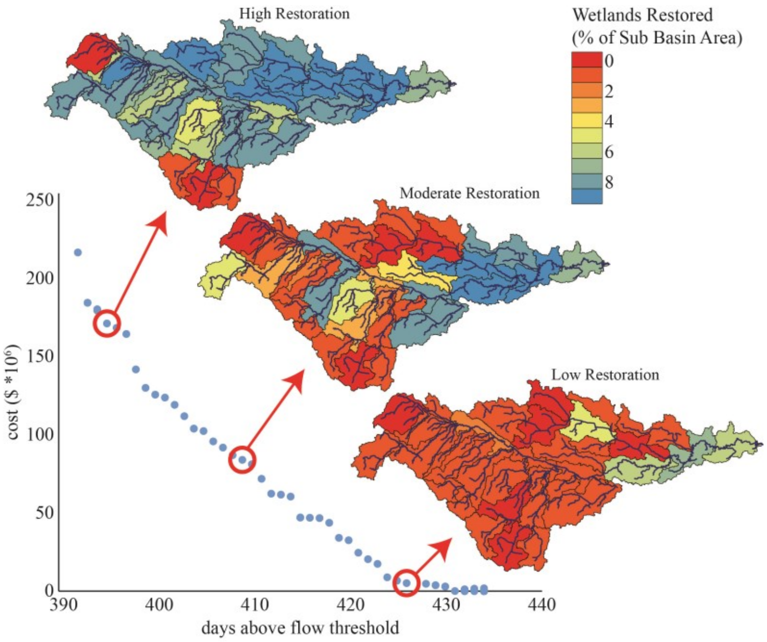

Figure 15. Preliminary results from application of a genetic algorithm approach for evaluating scenarios of wetland restoration. In each modeled sub basin, up to 9% of the landscape was allowed to be converted for the purpose of wetland restoration. For varying levels of wetland restoration, costs and associated reductions in peak flow were determined. For the Cottonwood River Basin, the most cost effective wetland restoration strategies focus on the downstream and main-stem portions of the watershed.

4.2. Network structure nitrate removal efficiency

A. Hansen, J. Czuba, E. Foufoula-Georgiou, and J. Finlay

Many agricultural landscapes of the Midwest, including the Minnesota River Basin, were once dominated by tall-grass prairie and dotted with poorly drained wetlands. Beginning in the late 1800s, these wetlands were drained for agriculture with the construction of surface ditches and installation of subsurface drain tiles. Only remnants of these wetlands remain today. However, where they do exist, they are important sources, sinks, and transformers of important macronutrients of carbon, nitrogen, and phosphorous. Specifically, the research by REACH members described in section 3 shows that wetlands (at least seasonally) are (1) a carbon source to downstream reaches, (2) decease nitrate possibly through assimilation or denitrification, and (3) are important locations of phosphorous storage and transformation between dissolved and particulate forms. *Thus, where these wetlands are located in the landscape has important implications for understanding downstream water quality.* We are actively developing network-based tools and models to better understand carbon, nitrogen, and phosphorous cycling at the watershed-scale (Czuba et al., 2016b). At the heart of this effort is quantifying how wetlands are arranged spatially and how they are connected to the river network. We can then incorporate the process-based knowledge gained on nutrient cycling (see section 3) into a network context for informing how the existing configuration of lakes/wetlands (Fig. 16) affects nutrient delivery. The ultimate goal of this research is to identify where to target management actions, in terms of creating wetlands, in order to improve water quality. A potential extension of this work is to understand how changes in the water, sediment, and nutrient regimes cascade to changes in the community of aquatic biota, such as algae, insects, mussels, and fish, all within a network context.

Figure 16. Wetland/river network complex of in the Le Sueur Basin. River channels are shown in dark blue, lakes/wetlands directly connected to the river network are shown in light blue, isolated lakes/wetlands are shown in dark green, and the basin outlet is indicated by a red triangle.

4.3. Evaluation of trade-offs associated with wetland interventions

B. Keeler, P. Hawthorne, S. Polasky, E. Foufoula-Georgiou, P. Belmont, A. Hansen, and J. Czuba

Our WSC-REACH project, focused in the Minnesota River Basin, has made breakthrough discoveries in monitoring and modeling the effects of climate and land-use change on the water cycle, river channel and floodplain dynamics, water quality, and aquatic life. It also has exposed our fundamental knowledge gaps on how the interconnected system of Food-Energy-Water (FEW) works and the need for such an understanding to drive sustainable environmental and economic outcomes. *This research is part of a supplement to our project that aspires to lay the foundation in advancing a FEW systems-level thinking for agricultural landscapes by focusing on identifying and quantifying the challenging links between policy, markets, climate drivers, land and water management actions, and the cascade of environmental implications.* We aim to achieve two goals: (1) assess the benefits and costs of alternative futures for the MRB, including impacts to ecosystem services across spatial and temporal scales and (2) incorporate these impacts into a generalizable framework that links policy, markets, and climate drivers, to land and water management actions, to the nonlinear cascade of environmental implications, to a socio-economic valuation of changes in ecosystems, back to potential policies, payments or incentive schemes needed to shift underlying drivers of behavior and resilience of the FEW system (Fig. 17).

The economic benefits of sediment reduction and other wetland services are poorly quantified. In general, there is a lack of guidance in the ecosystem services literature on how to do sediment valuation well. Most researchers rely on benefits transfer or willingness to pay studies to estimate sediment value. *We are initiating a full cost accounting of sediment costs and benefits.* Our work will focus on the MRB, but include a broader review and interpretation of sediment-related costs. We will review the literature on sediment value and costs, interview experts in the MRB and elsewhere about the biophysical and economic assumptions needed to estimate costs, and propose a comprehensive framework for the accounting of sediment value. The outcome of this work will be a "go-to" reference for sediment valuation that updates and expands the scope of previous literature. Our focus will not be on generating sediment values specific to the MRB, but rather producing a synthetic and comprehensive reference that will make a useful and needed contribution to the ecosystem services literature.

The second part of this effort will result in a visualization of trade-offs. Models developed by the REACH team can evaluate how wetland interventions will affect a variety of objectives of interest to stakeholders such as nitrate removal, sediment, DOC, mussels, peak flow, etc. How do these various objectives trade off? How much of one objective do you have to give up to get more of another objective? For example, if you prioritize wetlands for denitrification how much sediment retention (via high flow reduction) do you lose? What are the opportunities for win-wins and where are there tradeoffs? How do we prioritize wetlands that maximize benefits at minimal costs? How can we engage stakeholders in prioritizing some objectives over others and expressing values or weights? What does an optimal scenario of wetland restoration for multiple objectives look like? We are leveraging methods already developed in our group on visualizing tradeoffs to multiple objectives and developing optimized portfolios of restoration interventions. We will apply this optimization approach to the outputs of REACH models to generate efficiency frontiers that visualize how different objectives (water quality, carbon, habitat, peak flow, etc) tradeoff with each other. These frontiers can be useful in assigning weights to different objectives and then generating "optimal" landscapes that maximize objectives given user-defined constraints (budget, area, etc). The outcome of this work will be efficiency frontiers and optimized wetland intervention portfolios (aggregated by subwatershed, HUC, or other unit of interest). These biophysical results can be combined with cost data and agricultural production value to assess how different scenarios affect the distribution of private vs. public benefits.

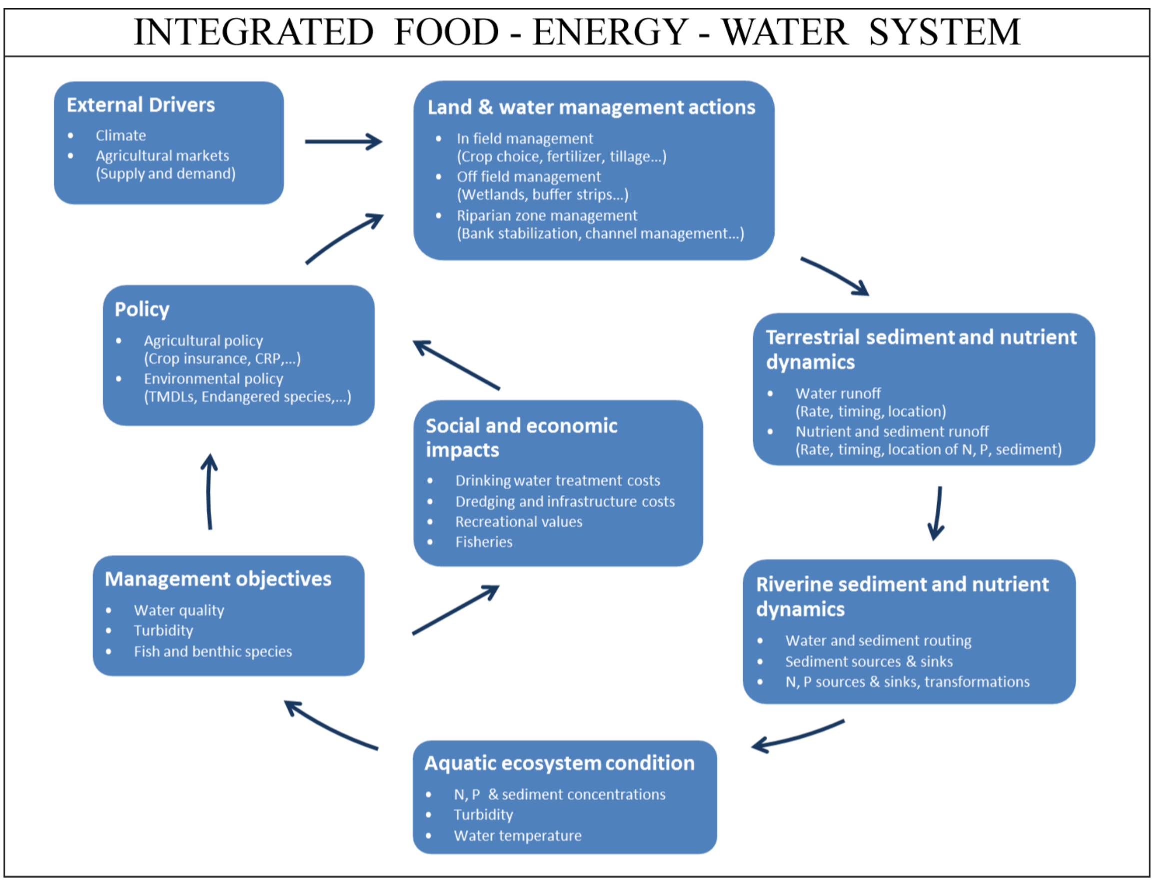

Figure 17. The proposed framework for studying the integrated FEW system of agricultural landscapes.

5. Engaging and educating the public

5.1. Socio-scientific issues

G. Roehrig, E. Karahan, S. Andzenge, and N. Ghalichi

Our curriculum development and associated research has focused on socio-scientific issues (SSIs) to promote teaching and learning of environmental science in the context of the Minnesota River Basin. One of the essential outcomes of K-12 science education is to enable students to use their understanding of science to contribute to public debate and make informed decisions about SSIs that impact their lives. Students need to be able to assess the risks and benefits of alternative solutions, pose questions, and evaluate the integrity of evidence and counter evidence in order to make well-informed decisions. Science is a discipline that relies on empirical evidence and formal reasoning that depends on logical and mathematical concepts and the processes of induction or deduction. However, SSIs are interpreted in a creative fashion and variations in scientific reasoning are not fully able to explain conclusions reached because the explanation lies in a reality, which is much less objective. Moreover, the decision-making processes in SSIs are different and more complicated from those involved in reaching conclusions regarding purely scientific questions.

Research in SSI-based interventions is relatively new, and there is a need for understanding more about the effects of SSI-based learning environments. Despite the growing body of literature in SSI, only a few researchers have gathered empirical data on the effects of SSI-based learning environments. In response to this need, we have developed SSI-based curriculum in collaboration with local environmental science teachers and our research has explored how students respond to teachers' practices of teaching SSI. Our results working in four different high school environmental science classrooms show that in order to actively participate in an SSI-based investigation and decision-making processes, students needed to utilize multiple reasoning modes and interdisciplinary thinking. Students, who were exposed to more traditional data-driven SSI instruction, mostly reasoned scientifically about the sediment load issues in the Minnesota River. In contrast, students who experienced SSI instruction with the inclusion of social domains, such as ethics and economics, and student-driven community involvement projects showed multiple reasoning modes, including scientific, social-economic, ethical, and ecological reasoning modes, in their decision-making about the sediment load issue in the river. Comprehensive, semester-long SSI content integration that incorporates social and ethical domains resulted in higher-level socio-scientific reasoning for students which is critical when considering the need to increase scientific literacy and public engagement in scientific issues such as sediment load.

Associated research has explored how a SSI-based environmental science class can be structured for promoting the agency of the students. Agency is defined as purposeful actions taken by a student in their own interest or capacity to make choices and act on these choices in a way that makes a difference. Our goal here was to empower students to act on their learning around issues within the Minnesota River Basin. Teachers who used the multifaceted and interdisciplinary nature of a SSI were able to empower their students to select and act on environmental issues based on their personal interests. As a result, the students were more motivated and encouraged to make differences in the society they lived in by using the community-based projects for improving the quality of the environment surrounding them.

5.2. Curriculum development and classroom implementation

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Examples of developed curricula can be found on the project site at this link (http://stem-projects.umn.edu/riverrun/test-page/). On-going work is exploring the development of an interactive, online computer-simulation tool that allows students to explore the impact of land-management practices on nitrate levels. The basis for this computer-simulation tool is the research of REACH members described in section 4.2.

Additionally, we are reworking scientific articles related to the WSC scientific research into formats accessible for students and classroom use. This approach is grounded in a framework of disciplinary literacy which promotes student learning in how to read, think about, write, communicate, and use information like a scientist. By promoting engagement in these processes, disciplinary literacy builds an understanding of how knowledge is produced rather than just the knowledge in and of itself. Our adapted primary literature products will retain the characteristics of the primary published literature but be accessible and understandable to K-12 students.

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