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

REACH (REsilience under Accelerated CHange)

Year 3 Progress Report for 2014–2015

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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. Biweekly cyberseminars were held between all participating institutions. Presentations were given by PIs, post-docs, and graduate students, in addition to external presenters. These meetings are held through an interactive web-based conference system to allow for ample discussion and interaction.
2. A 3-day annual collaboration meeting was held in August 2014 at the University of Minnesota in Minneapolis, MN, to bring PIs and their research groups together to discuss action plans for the greater collaborative effort.
3. 34 Presentations were given this past year at local, regional, national, and international conferences including: annual meetings of the American Geophysical Union, European Geosciences Union, Geological Society of America, Society for Freshwater Science, National Association of Research in Science Teaching, European Science Education Research Association, and Association for Educational Communications and Technology; Joint Aquatic Sciences Meeting; Mississippi River Education Symposium; SEDHYD 2015: joint 10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference; Gordon Research Seminar; University of Minnesota Water Resources Sciences Program: Seminar series; Deltas in Times of Climate Change II International Conference; MNeLearning Summit; Minnesota Water Resources Conference; Upper Midwest Stream Restoration Symposium; and University of Minnesota's Institute on the Environment Sustainability Symposium.

(2) Educational activities

The third 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. Specific activities have included (*see attached pdf for a brief summary of these educational activities*): 1. Continued collaboration with K-12 educators as part of the River Run Team; 2. Developing and implementing curricula focused on socio-scientific issues in the MRB; 3. Collaboration and collection of digital artifacts via a developed online space; and 4. A focus on integrating socioscientific issues and technology in science curricula.

(3) Stakeholder meetings

Stakeholder meetings were held by multiple REACH PIs through the Collaboration for Sediment Source Reduction (CSSR) during August 2014 and January 2015 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. Two stakeholder meetings remain, 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:

(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.

1.2.2. Significant results:

Research activities primarily focused on understanding how changing watershed hydrology, nutrient loading, and sediment dynamics affect ecosystem processes (and degradation) in the MRB. During the third year, research projects included synthesis and analysis of existing monitoring data, developing framework models for river networks and routing specific to the MRB, and field data collection to better understand linkages between the physical and biological systems.

Research activities undertaken in 2014-2015 include (*see attached pdf for a brief summary of these research topics*):

1. **A network approach to river basin vulnerability assessment.** We developed a modeling framework by which a landscape is decomposed into a connected network of elements including river channels, wetlands, agricultural fields, etc., each receiving a space-time variable input of water and sediment, which are then tracked through a dynamic process-based approach. By placing dynamical processes occurring at small scales into a network context, it is possible to better understand how reach-scale changes cascade into network-scale effects, useful for informing the large-scale consequences of local management actions.

2. **Effect of agricultural drainage on hydrologic response**. We have quantified the detailed nature of hydrologic change due to agricultural practices and climate change in the MRB. Our analysis has revealed a changed storage-discharge relationship during the growing season, sharper rising limbs of daily streamflow hydrographs and stronger dependence on previous-day precipitation. Considering the combined climate-drainage effects, we have shown that artificial drainage has reduced the inherent nonlinearity of daily streamflow dynamics, perhaps reflecting the reduced complexity of the engineered hydrologic system.

3. **Expression of geologic controls on multi-scale river network structure.** We investigated how the multi-scale variability of landscapes depicts the pronounced regularities that, under the influence of geologic controls, break away from the typical "cascade of energy" and self-similarity of typical landscapes. We showed how the competition for space in steeper parts of the landscape left behind from the last glaciation period resulted in channel geometry and length-area relationships different from those expected in unconstrained landscapes.

4. **Meandering river dynamics.** We demonstrated via analysis of simulated meandering rivers that the static planform geometry of a cut-off meander bend contains the history of its evolution and that individual meander bends are most sensitive to perturbations early in their lives. This result may aid decision makers when considering dam and bridge constructions, dredging and bank armoring.

5. **Integrative hydro-geo-biological predictive modeling.** We developed a process-based dynamic interaction model of streamflow-sediment-phytoplankton-fresh water mussel population dynamics and used it to understand how changes in streamflow might lead to extirpation or carrying capacity in its long-term native mussel population. We calibrated the model in several sites in the MRB and demonstrated its predictive ability and also its potential as a tool to examine how changes in hydrology and/or sediment production might lead to potential ecological regime shifts.

6. **Understand sediment sources in the MRB.** Using a combined approach of field-monitoring and modeling, we have developed budgets of suspended sediment in several basins of the MRB. The goal is to understand the sediment sources, pathways, and depositional sinks in the MRB and how these might be affected by the underlying geology and geomorphic history of the basin. Specific results for suspended sediment production from bluffs and knickzones have been obtained, forming an important element for developing management plans for sediment reduction studies.

7. **Potential effect of wetland restoration for peak flow and sediment reduction**. We have shown that hydraulic conductivity is one of the main limiting factors in peak flow and sediment loading rate reductions offered by wetland restoration. Using modeling-based and empirical relationships between wetland surface area and contributing watershed areas, as well as between peak flows and wetland extent, we have developed a reduced complexity model that can be used as a tool to examine the trade-offs between percent area covered by wetlands and wetland hydraulic conductivity in optimally achieving desirable peak flow and sediment reduction.

8. **Eco-geomorphic response to changing flows.** We have carried out laboratory and field experiments to understand and quantify the relationships among vegetation establishment, hydrology, and sediment transport towards guiding management actions and the identification of priority management zones to reduce sediment related impairments. Our work has shown that riparian vegetation is the primary control on river morphology by adding surface cohesion and by trapping and storing suspended sediment and that the dynamic interaction of hydrology with point bar vegetation during low and high flows plays a significant role in determining the long-term ecological and sedimentological state of the river.

9. **Large scale watershed nutrient mass balance analysis.** We have analyzed annual watershed loading data and built mass balances to identify factors that lead to nutrient retention or stream losses in the MRB. We have shown that variation in precipitation and land use intensity are important in determining how much N is taken up or denitrified in watersheds, and that lakes and wetlands are important sinks for inorganic N in agricultural areas. We now examine the inter-annual variability of N and P exports driven by climate, and also factors that regulate P retention.

10. **Sources, sinks, and controls of N and P in agricultural watersheds.** From samples across 94 watersheds we documented a significant negative relationship between nitrate concentration and percentage of drainage area that is wetlands or lakes, while no significant relationship was found between nitrate concentration and drainage area. Our sampling in 10 sites over time showed that wetlands suppress current N losses in the spring time period and increase levels of dissolved organic carbon (DOC) which may enhance denitrification downstream. This analysis suggests that small to modest increases in wetland cover could have strong positive impacts on N retention.

11. **Patterns and processes affecting biotic structure in agricultural drainage networks.** The variations and transport of organic matter in streams and rivers likely have important consequences for ecosystem processes and biota. Especially, filter-feeding and collecting microinvertebrates are two groups of biota that feed on suspended and deposited particulate organic matter. Thus, their growth might reflect the patterns and variability of flow conditions and organic matter and lead to eliciting the linkages between physical processes, such as hydrology and sediment transport, and biologic processes, such as the structure and function of food webs and the carbon that supports them.

12. **Integration of MRB socio-scientific issues in K-12 science education.** We use the science context of the MRB to communicate to K-12 students and the general public the important aspects of land use and climate change affecting our environment. We have developed curriculum material for classroom implementation, continued the teacher training summer workshops, and advanced the “The River Run: Professional Development with a splash of Technology” program.

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 1 research associate, 4 post-docs, 16 graduate students, and 6 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 organize and attend our collaboration's biweekly cyberseminars and cyber-learning sessions, and are given the opportunity to present their research. Post-docs and graduate students are also given the opportunity to attend our annual collaboration meetings and present their research there as well. In 2015 our annual collaboration meeting will be held at the Institute on the Environment of the University of Minnesota in St. Paul, MN.

This grant is also providing training opportunities for 6 K-12 educators through our River Run initiative. During year 3 (2014-2015), professional development experiences for the River Run Team included (Date - ***Event*** - Description):

1. Aug. 4-6, 2014 – ***Active Learning Experience*** - Immersion experience targeted specifically to secondary science teachers. Grounded within place-based and active learning frameworks, workshop topics included instructional strategies and activities for teaching and learning about: formation and ecology of rivers and watersheds, causes and contributors to turbidity, historical, cultural, agricultural development of river civilizations.
2. Aug. 6-7, 2014 – ***Curriculum Development*** - Development of content knowledge specific curriculum geared towards teaching and learning about environmental science within the context of the Minnesota River Basin (MRB).
3. Aug. 7, 2014 – ***Teacher Enrichment*** - Extensive tour the St. Anthony Falls Laboratory (SAFL) research and educational facility. Session emphasis on the availability of SAFL research and facilities to support teaching environmental science relevant to the contexts of MRB secondary science learners.
4. Oct. 2014 - June 2015 – ***On-going coaching and support*** - Periodic check-in via face-to-face, email, and telephone.
5. December 2014 – ***Fall Semester Meeting*** - Co-constructed a platform for spring 2015 pilot of teaching and learning environmental science grounded within a service learning framework.
6. May 2015 – ***Spring Semester Meeting*** - Reflection on practice: successes, learning opportunities, direction forward using service learning as a framework for teaching and learning environmental science within the context of the Minnesota River Basin.

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 year, 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, with potential expansion of the team to include additional secondary environmental science teachers. 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. Lastly, 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 two stakeholder meetings 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.

Specific research goals to be pursued in the fourth year include (see supplemental document for more information):

1. Investigate the transport of sediment (and other material) along the river network using a minimal complexity, simple predictive framework, relax some of the assumptions to include storage and space-time variable release of sediment, and test this against available data. Use this approach to investigate management actions and vulnerability/resilience questions to future changes in the MRB.
2. Extend the network-based model to include water retention basins for modeling nutrient and fine sediment transport in a watershed to guide mitigation and planning strategies, i.e., where and with what properties to locate retention basins for achieving desired objectives.

3. Further quantify the effect of tile drainage on the basin hydrologic response at multiple scales (daily up to weekly) by performing analysis of several sub-basins within the MRB and relating the results to land use change.
4. Understand how river networks not obeying the typical self-similar structure can be modeled via extended forms of higher-order branching structure topologies.
5. Test the connections found between simulated planform geometries and migration dynamics using real data from Landsat imagery – for this, one of the most rapidly migrating rivers of the world (Ucayali River in Peru) has been selected for analysis.
6. Further understand how natural meander migration is affected by constraints imposed by human factors and how these external perturbations propagate throughout the system to change the dynamics of meander growth and cut-offs.
7. Theoretically study the non-linear dynamics and threshold behavior (two states of attraction) of the developed hydrologic-ecologic model and understand what parameters or model component parameterizations mostly control the long-term behavior.
8. Net Anthropogenic Phosphorus Input (NAPI) calculations are ongoing and will be used with watershed phosphorus (P) loading data to analyze factors that regulate P retention across watersheds. Examination of interannual variability in N and P export driven by climate is planned using the multi watershed database described above, as well as analysis of the factors controlling the specific forms of N and P exported (i.e. organic vs. inorganic nitrogen, and dissolved vs. particulate P).
9. Continue field sampling in summer 2015 of biological processes and physical characteristics to understand whether benthic biological processes have a continuous or threshold response to physical conditions, and how upstream lakes or wetlands modify these relationships.
10. Continue sampling of macrovinvertebrates above and below wetlands in the Le Sueur watershed, in conjunction with water quality and habitat data, with the goal of determining whether variation in macroinvertebrate diversity or trophic structure can be linked to wetland-mediated changes in stream condition.
11. Finalize sediment budgets for Blue Earth River and Watonwan River, pending sediment fingerprinting data. Utilize sediment budget information to help constrain a sediment delivery model and use it with stakeholder groups to make decisions about management options for managing both peak flows and excess fine sediment loading within the watershed.
12. Analyze sub-basin response by geomorphic regime. Merge reduced complexity hydrologic response model with sediment simulation model to connect land use decision with hydrologic response with geomorphic response.
13. Complete field data collection and OSL analyses on relict channels preserved on terraces throughout the lower Minnesota River basin to determine paleogeometry and paleodischarge throughout the Holocene. Reconstruct history of channel incision on Blue Earth and Watonwan Rivers.

14. Conduct series of physical experiments to investigate the fine sediment trapping efficiency of emergent vegetation. Relate how changing germination and growth patterns may feedback on overbank deposition rates in the lower Minnesota River.
15. Continue data collection from teacher classrooms (classroom observations, teacher interviews, classroom artifacts, student interviews). Continue the collection of data related to the integration of technology by teachers in selected classrooms to reveal teachers technological pedagogical content knowledge.
16. Continue work on an integrative watershed model for use by multiple REACH PIs.

Supporting Files

PDF Uploaded

PRODUCTS – What has the project produced?

Books:

Book Chapters:

Peer-Reviewed Journal Articles:

Bode, C.A., M.P. Limm, M.E. Power, and J.C. Finlay. 2014. Subcanopy Solar Radiation Model: Predicting solar radiation across a heavily vegetated landscape using LiDAR and GIS solar radiation models. *Remote Sensing of the Environment* 154: 387–397 10.1016/j.rse.2014.01.028

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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.*, *under review*.

Guentzel, K.S., M Hondzo, B.D. Badgley, J.C. Finlay, M.J. Sadowsky, and J.L. Kozarek. 2014 Measurement and modeling of denitrification in sand-bed streams of varying land use. *Journal of Environmental Quality* 43:1013–1023 10.2134/jeq2013.06.0249

Hansen, A. T., J. A. Czuba, J. Schwenk, A. Longjas, M. Danesh-Yazdi, D. J. Hornbach, and E. Foufoula-Georgiou (2015), Coupling freshwater mussel ecology and river dynamics using a simplified dynamic interaction model, *Freshwater Science*, *to appear.*

Hobbie, S.E., L.A. Baker, C. Buyarski, D. Nidzgorski, and J.C. Finlay. 2014. Decomposition of tree leaf litter in a street: implications for urban water quality. *Urban Ecosystems*. 17 (2): 369-385 DOI 10.1007/s11252-013-0329-9

Hood, J.M., C.F.McNeely, J.C. Finlay, and R.W. Sterner. 2014. Influence of diet stoichiometry on nutrient release rates and ratios of selectively feeding detritivores. *Freshwater Science* 33(4):1093–1107

Janke, B., J.C. Finlay, S. E. Hobbie, L. A. Baker, D. Nidzgorski, R. W. Sterner, and B. N. Wilson. 2014. Contrasting Influences of Stormflow and Baseflow Pathways on Nitrogen and Phosphorus Export from an Urban Watershed. *Biogeochemistry* 121(1):209-228 10.1007/s10533-013-9926-1.

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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.

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Walter Anthony, K.M, S.A. Zimov, G. Grosse, M.C. Jones, P. Anthony, F. S. Chapin III, J.C. Finlay, M.C. Mack, S. Davydov, P. Frenzel, S. Frolking. 2014. A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature* 511: 452-456 10.1038/nature13560

Whittinghill, K.A., J.C. Finlay, and S.E. Hobbie. 2014. Bioavailability of dissolved organic carbon across a hillslope chronosequence in the Kuparuk River region, Alaska. *Soil Biology & Biochemistry* 79: 25-33.

Thesis/Dissertations:

Bevis, M, 2015, Pleistocene base-level fall is a fundamental driver of erosion in southern Minnesota's greater Blue Earth River basin. M.S. Thesis: University of Minnesota Duluth, 96 p + digital archive.

Karahan, E (2015). Secondary School Teachers' Expereinces of Designing and Teaching Sociocientific Issues-Based Classes and their Students' Understanding of Science and Socioscientific Reasoning. Doctoral Dissertation, University of Minnesota.

Triplett, L., 2015. Variation in vegetation establishment, hydrologic regime, and sediment transport within the Minnesota River basin. M.S. Thesis: University of Minnesota, St. Paul, MN. 120 p.

Conference Papers and Presentations:

Andzenge, S.T., Karahan, E., Roehrig, G. (July, 2015). Digital Natives, Immigrants, and TPACK: an exploration of secondary science teachers and technology. Paper presentation (accepted) at the annual MNeLearning Summit, Minenapolis, MN.

Andzenge, S.T., Karahan, E., Bhattacharya, D., Roehrig, G. (April 2015). Eliciting students' understanding of river geography and socioscientific issues through a critical response protocol. Paper accepted for presentation at the annual meeting of the National Association of Research in Science Teaching (NARST), Chicago, IL.

Andzenge, S.T., Karahan, E., Bhattacharya, D., Roehrig, G. (November 2014). Technology integration and water sustainability in STEM education: A professional development experience. Paper presented at the annual meeting of the Association for Educational Communications and Technology (AECT), Jacksonville, FL.

Batts, V., Triplett, L., Gran, K. B., Lenhart, C. (2014). Riparian Vegetation, Sediment Dynamics and Hydrologic Change in the Minnesota River Basin. American Geophysical Union annual meeting, San Francisco, CA.

Bevis, M., Gran, K. (2014). Fluvial adjustment to Pleistocene base-level fall affects sediment budgets of Minnesota River tributaries. Geological Society of America Annual Meeting, Vancouver, BC.

Bevis, M., Gran, K. (2014). Improving the sediment budgets of Minnesota River tributaries with statistical analyses of reach-averaged variables. Minnesota Water Resources Conference, St. Paul, MN.

Bevis, M., Gran, K. (2015). Sediment budgets for the Greater Blue Earth River Basin: Pleistocene base-level fall drives near-channel erosion. Presented at the Upper Midwest Stream Restoration Symposium, Dubuque, IA.

Boardman, E & J. Finlay 2015 Controls over watershed nitrogen retention. The Society for Freshwater Science 2015 Annual Meeting.

Czuba, J.A., E. Foufoula-Georgiou, K.B. Gran, P. Belmont, and P.R. Wilcock (2015), Sediment dynamics on river networks: incorporating sources, stores, and sinks from a sediment budget into a network-modeling framework, SEDHYD 2015: joint 10th Federal Interagency Sedimentation Conference and 5th Federal Interagency Hydrologic Modeling Conference, Reno, Nevada, 19-23 April.

Czuba, J.A., and E. Foufoula-Georgiou (2015), Identifying emergent physical, chemical, and biological hotspots for guiding sustainable landscape management, Institute on the Environment Sustainability Symposium, St. Paul, Minnesota, 10 April.

Czuba, J.A., and E. Foufoula-Georgiou (2014), Network dynamic connectivity for identifying hotspots of fluvial geomorphic change, EP33A-3605, AGU Fall Meeting, San Francisco, California, 15-19 December.

Danesh-Yazdi, M., A. Tejedor, R. Schumer, and E. Foufoula-Georgiou (2014), Self-dissimilar Landscapes: Probing into Causes and Consequences via Multi-scale Analysis and Synthesis, AGU Fall Meeting, San Francisco, California, 15-19 December.

Danesh-Yazdi M., E. Foufoula-Georgiou, and D.L. Karwan, Time-Variant Travel Time Distributions in a Subsurface-Drained Watershed, Catchment Science: Interactions of Hydrology, Biology & Geochemistry – Gordon Research Seminar, Proctor Academy, Andover, New Hampshire, 13-14 June.

Dolph, C. A. Hansen & J. Finlay 2015 Trophic dynamics in agricultural streams: longitudinal and temporal patterns in carbon and nitrogen isotope ratios of benthic macroinvertebrates from the Minnesota River Basin, US. The Society for Freshwater Science 2015 Annual Meeting.

Foufoula-Georgiou, E. (2014), Belmont Forum Deltas Project (BF-DELTAS) – to sustain the resilience of deltas, Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September.

Foufoula-Georgiou, E., A. Tejedor, A. Longjas, I. Overeem, F. Renaud and J. Dearing (2014), Constructing vulnerability maps of material and energy pathways in deltas, Deltas in Times of Climate Change II International Conference, Rotterdam, Netherlands, 24-26 September.

Foufoula-Georgiou, E. (2014), Mathematical Hydrology and Vulnerability Science: the come-back of a systems approach for Sustainability, AGU Fall Meeting, San Francisco, California, 15-19 December [INVITED].

Gran, K. B., Batts, V. A. (2014). Physical models in geomorphology education: Lessons from the stream table. Geological Society of America Annual Meeting, Vancouver, BC.

Hansen A.T., J.A. Czuba, J. Schwenk, A. Longjas, M. Danesh-Yazdi, D.J. Hornbach and E. Foufoula-Georgiou (2015), Coupling freshwater mussel ecology and river dynamics using a simplified dynamic interaction model, Society for Freshwater Science Annual Meeting, Milwaukee, Wisconsin, 17-21 May.

Hansen, A.T., Finlay, J.C., 2014, Controls on Aquatic Nitrogen Uptake within an Agricultural Watershed. Joint Aquatic Sciences Meeting, May 18-23, 2014, Portland OR.

Hansen, A.T., Finlay, J.C. 2014, Biological nitrogen uptake in agriculturally influenced Minnesota streams and rivers. University of Minnesota Water Resources Sciences Program: Seminar series. April 25, 2014, St. Paul MN.

Harrison, I.J., E. Foufoula-Georgiou, and B. Burkholder (2014), Catalyzing action towards sustainability of deltaic systems in collaboration with colleagues in the Belmont Forum DELTAS project. IUCN World Congress on Protected Areas. Stream 4: Supporting Human Life, 18 November.

Karahan, E., Andzenge, S.T., Roehrig, G. (August 2015). Engaging students in community-based issues through authentic problem-based learning experiences. Paper presentation (accepted) at the annual meeting of the European Science Education Research Association (ESERA), Helsinki, Finland.

Karahan, E., Andzenge, S.T., Bhattacharya, D., Roehrig, G. (November 2014). A technology rich professional development program and its influence on participant teachers' practices. Paper presented at the annual meeting of the Association for Educational Communications and Technology (AECT), Jacksonville, FL.

McFadden, J. (November 2014).The River Run: Professional development with a splash of technology. Mississippi River Education Symposium, East Alton, IL.

Mitchell, N., Cho, S.J., Dalzell, B., Kumaraswamy, K., and Gran, K. (2015). Modeling Stream Management through Spatially Distributed Water Control Structures in the Le Sueur Watershed with SWAT. Presented at the Upper Midwest Stream Restoration Symposium, Dubuque, IA.

Mitchell, N. A., Cho, S. J., Dalzell, B. J., Kumaraswamy, K., Gran, K. (2014). Modeling the hydrological effects of wetland restoration in the Le Sueur watershed with SWAT. Geological Society of America Annual Meeting, Vancouver, BC.

Mitchell, N.A. (2014), Modeling the hydrological effects of wetland restoration in the Le Sueur watershed with SWAT. Minnesota Water Resources Conference, St. Paul, MN.

Schwenk, J., E. Foufoula-Georgiou, and S. Lanzoni (2014), Revisiting nonlinearity in meandering river planform dynamics using Gradual Wavelet Reconstruction, AGU Fall Meeting, San Francisco, California, 15-19 December.

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.

Takbiri, Z., J.A. Czuba, and E. Foufoula-Georgiou (2014), Complex hydrologic changes in frequency-magnitude response due to shifting agricultural practices in the Midwestern US, AGU Fall Meeting, San Francisco, California, 15-19 December.

Targos, C., Gran, K. B. (2014). Estimations of paleochannel geometry and discharge using Ground Penetrating Radar (GPR) on terraces of the Le Sueur River, south-central Minnesota. American Geophysical Union annual meeting, San Francisco, CA.

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

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

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.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS – Who has been involved?

What individuals have worked on the project?

Efi Foufoula-Georgiou (PI)

Jacques C Finlay (PI)

Karen B Gran (PI)

Gillian H Roehrig (PI)

Laura Triplett (assistant professor)

Brent Dalzell (research associate)

Amy Hansen (post-doc)

Anthony Longjas (post-doc)

Alejandro Tejedor (post-doc)

Christy Dolph (post-doc)

Jonathan Czuba (graduate student)

Mohammad Danesh-Yazdi (graduate student)

Jon Schwenk (graduate student)

Zeinab Takbiri (graduate student)

Evelyn Boardman (graduate student)

Anika Bratt (graduate student)

Martin Bevis (graduate student)

Nathaniel Mitchell (graduate student)

Grant Neitzel (graduate student)

Courtney Targos (graduate student)

Virginia Batts (graduate student)

Laura Triplett (graduate student)

Senenge Andzenge (graduate student)

Devarati Bhattacharya (graduate student)

Engin Karahan (graduate student)

Justin McFadden (graduate student)

Katie Kemmit (undergraduate student)

Erika Senyk (undergraduate student)

Andrea Keeler (undergraduate student)

Kaitlin Johnson (undergraduate student)

Aaron Knowlton (undergraduate student)

Emily Ford (undergraduate student)

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

What other collaborators or contacts have been involved?

Nothing to report.

<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 and also lead the bi-weekly cyberseminar series of the REACH project.

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. REACH PIs played a significant role in a recent change in suspended sediment regulations in the state of Minnesota. Specifically, the Minnesota Pollution Control Agency (MPCA) recently converted from a turbidity- to TSS-based standard to define impaired waters under section 303d of the Clean Water Act. In making this conversion, the MPCA initially recommended a water quality standard of 30 mg/L for the Lower Minnesota

River Basin, which is comparable to the standard used for the Upper Mississippi River (above St. Paul, Minnesota) and is significantly lower than the 65 mg/L standard that applies to the rest of the Minnesota River Basin. Following a 9 page public comment on the proposed rule change in addition to phone calls and in-person meetings with PI Belmont to explain why the Lower Minnesota River Basin is geomorphically similar to the rest of the Minnesota River Basin (and naturally primed to generate more sediment than the upper Mississippi River), MPCA changed the regulatory standard to 65 mg/L for the entire Minnesota River Basin.

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

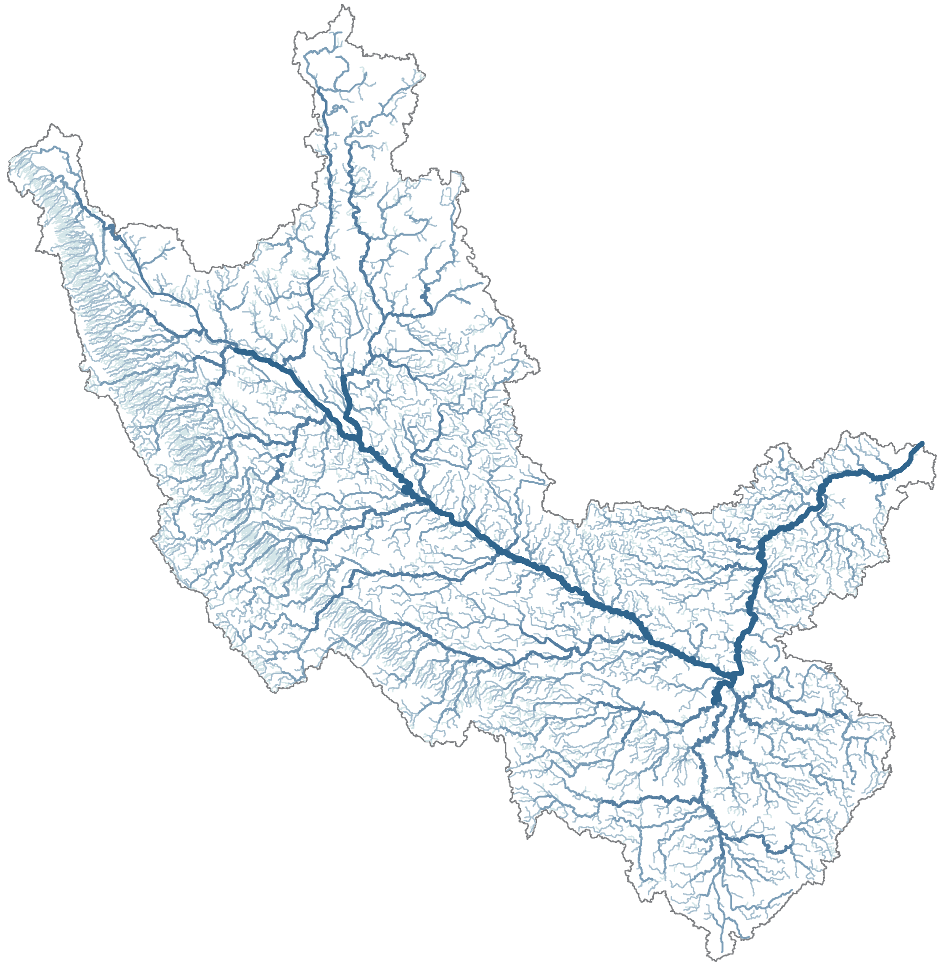
None

Significant changes in use or care of biohazards

None

REACH

Resilience under
Accelerated
Change



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

REACH (REsilience under Accelerated CHange)

Year 3 Research Summary for 2014–2015

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.

REACH principle investigators include:

Efi Foufoula-Georgiou – University of Minnesota

Jacques C. Finlay – University of Minnesota

Karen B. Gran – University of Minnesota – Duluth

Gillian H. Roehrig – University of Minnesota

Patrick Belmont – Utah State University

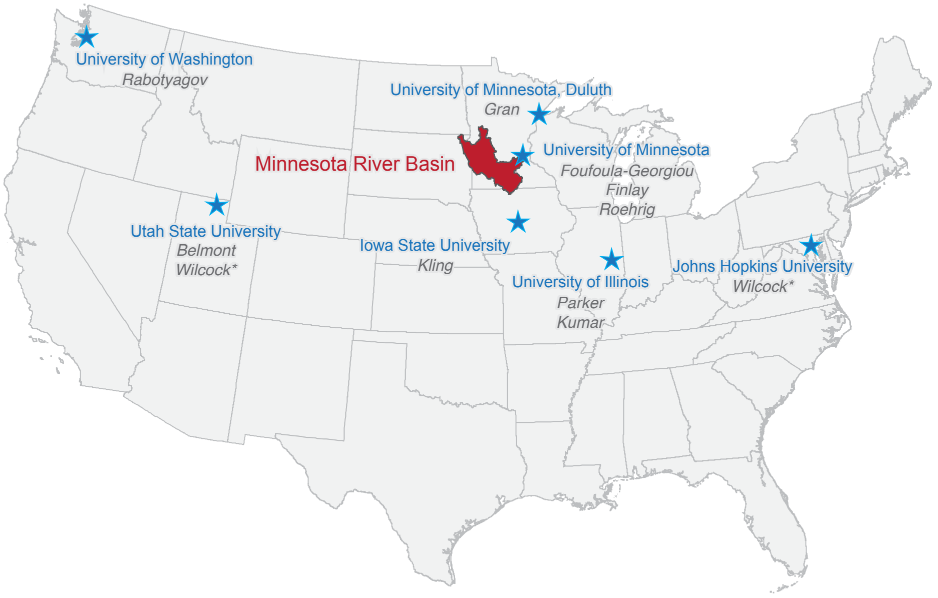
Peter R. Wilcock – Johns Hopkins University, now at Utah State University

Gary Parker – University of Illinois at Urbana-Champaign

Praveen Kumar – University of Illinois at Urbana-Champaign

Catherine L. Kling – Iowa State University

Sergey Rabotyagov – University of Washington



Efi Foufoula–Georgiou's group:

Jonathan Czuba, Mohammad Danesh-Yazdi, Amy Hansen, Anthony Longjas,

Jon Schwenk, Zeinab Takbiri, and Alejandro Tejedor

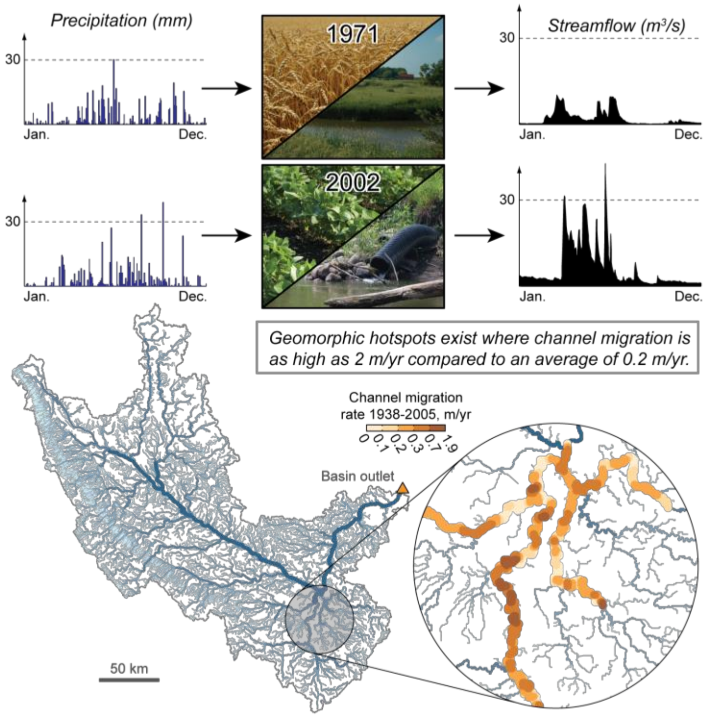
Research Themes and Accomplishments during 2014-2015

Our research efforts during the third year of the project continued on the overarching theme of understanding the hydro-geomorpho-ecological processes and feedbacks in an intensively managed agricultural landscape towards identifying vulnerabilities to change and informing management decisions. Specifically, our research concentrated on five main areas: (1) a network-based approach to river basin vulnerability assessment, (2) effect of agricultural drainage on hydrologic response, (3) expression of geologic controls on multi-scale river network structure, (4) meandering river dynamics, and (5) integrative predictive modeling of river hydro-geo-biological processes with emphasis on the effects of sediment change to riverine health. The developed frameworks and models, although general and transferable to other sites, were prototypes and tested in the Minnesota River Basin (MRB), which is the focus of the REsilience under Accelerated CHange (REACH) project funded under NSF's WSC program. We posit that such non-parametric analyses and reduced complexity modeling can provide more insight than highly parameterized models and can guide development of vulnerability assessment and integrated watershed management frameworks.

1. Network Approach to River Basin Vulnerability Assessment

Landscapes are too complex to be modeled with fully distributed deterministic models that consider all the small-scale physics and interactions and require as many as a hundred calibration parameters. Besides, changes in climate, land use, and water management impose non-stationary conditions, and nonlinearities in the system make it sensitive to uncertainties and small perturbations. Recognizing these limitations, we developed a simple network-based modeling framework [*Czuba and Foufoula-Georgiou*, 2014, 2015] that focuses on understanding and predicting the emergence of "hotspots of change" (Fig. 1) and captures the most important interactions and amplifications by exploring the system connectivity and its transport pathways including residence times, threshold behavior, and physical transformations.

The framework includes: (1) decomposing the landscape into a connected network of elements including river channels, wetlands, agricultural fields, etc., (2) spatially and temporally distributing inputs of water and sediment, and (3) tracking these inputs through individual landscape elements through process-based time delays. This framework has successfully identified vulnerable reaches of a river network prone to high rates of channel migration by highlighting where bed-material sediment has a tendency to persist and thereby encourage bank erosion [*Czuba and Foufoula-Georgiou*, 2015]. Furthermore, the framework has been used to unravel source contributions that synchronize on the network to form large clusters (i.e., areas of the network with high concentrations of flux) at channel migration hotspots (Fig. 2). Depending on network structure, process dynamics, and timing of arrival, the potential management options available may differ for reducing sediment generation of these specific source areas or for breaking the synchronization of these contributions before they coalesce into an aggregated mass. *By placing dynamical processes occurring at small scales into a network context using the dynamic connectivity framework, it is possible to better understand how reach-scale changes cascade into network-scale effects, useful for informing the large-scale consequences of local management actions*.



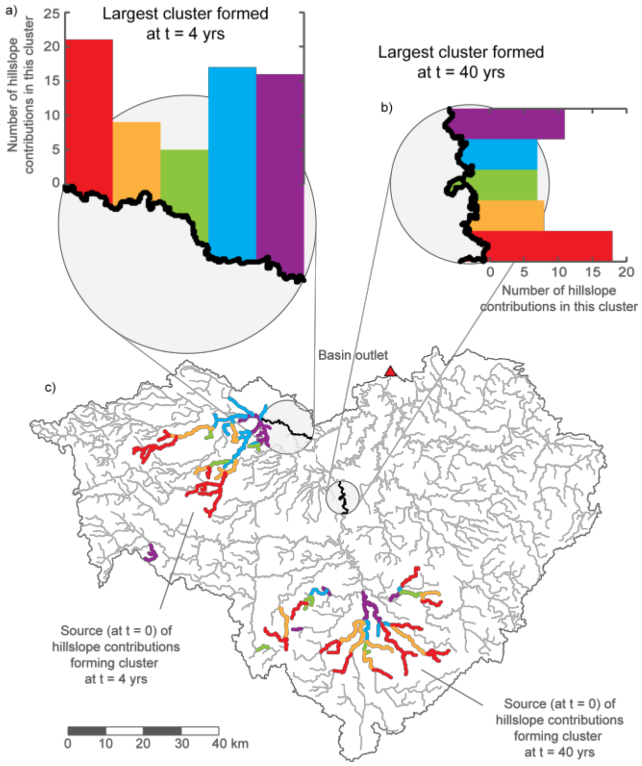


Figure 1. (Left) Agricultural land-use change has amplified streamflows in the MRB. Almost the same amount of precipitation in 1971 and 2002 resulted in a 3× increase in streamflow in 2002 (top). This amplification in streamflow is likely to concentrate physical, chemical, and biologic changes into "hotspots" (bottom), and the targeted management of these hotspots will most effectively improve the ecosystem.

Figure 2. (Right) Unraveling sediment sources that synchronize into "clusters" at locations of two channel migration hotspots. The largest cluster formed at time (a) 4 years (length ≈ 17 km) and (b) 40 years (length ≈ 15 km). The colored bars are the histogram of hillslope contributions within each cluster, where each color corresponds to a specific source area (at time 0) of the hillslope contributions composing the cluster, shown with the same colors in (c). This process-specific coarse-graining of the landscape allows the identification of space-time sources of sediment which eventually coalesce downstream due to the specific river network topology and flux dynamics.

2. Effect of Agricultural Drainage on Hydrologic Response

The hydrology of many agricultural landscapes around the world is changing in unprecedented ways due to the development of extensive surface and subsurface drainage systems to optimize productivity (Fig. 3). This plumbing of the landscape is altering water pathways, timing, and water losses creating new regimes of hydrologic response and driving a chain of environmental changes in sediment dynamics, nutrient cycling, and river ecology. Figure 3c demonstrates a pronounced spatial gradient in the progression of agricultural land-use change in the MRB. Agricultural transitions, defined as the year when the percentage of soybean cover exceeded that of hay and small grains as determined from the county level land use data (see Figures 3a-b), occurred from the late 1950s and early 1960s in the southeastern MRB to the 1990s and 2000s in the northwestern MRB. Studying the hydrology of basins which have already transitioned into a new agricultural regime is expected to provide much insight into the environmental future of the still-evolving basins.

We have proposed a framework to quantify the detailed nature of hydrologic change non-parametrically and study how this change might modulate ecological transitions [*Foufoula-Georgiou et al*., 2015]. Via time-frequency decomposition and a system's analysis approach of hydrograph slopes using Copulas, we quantify sharper rising limbs of daily streamflow hydrographs and stronger dependence on the previous-day precipitation, suggest a changed storage-discharge relationship, and show that the artificial landscape connectivity has most drastically affected the rainfall-runoff relationship at intermediate quantiles during the growing season (May-June) (Fig. 4).

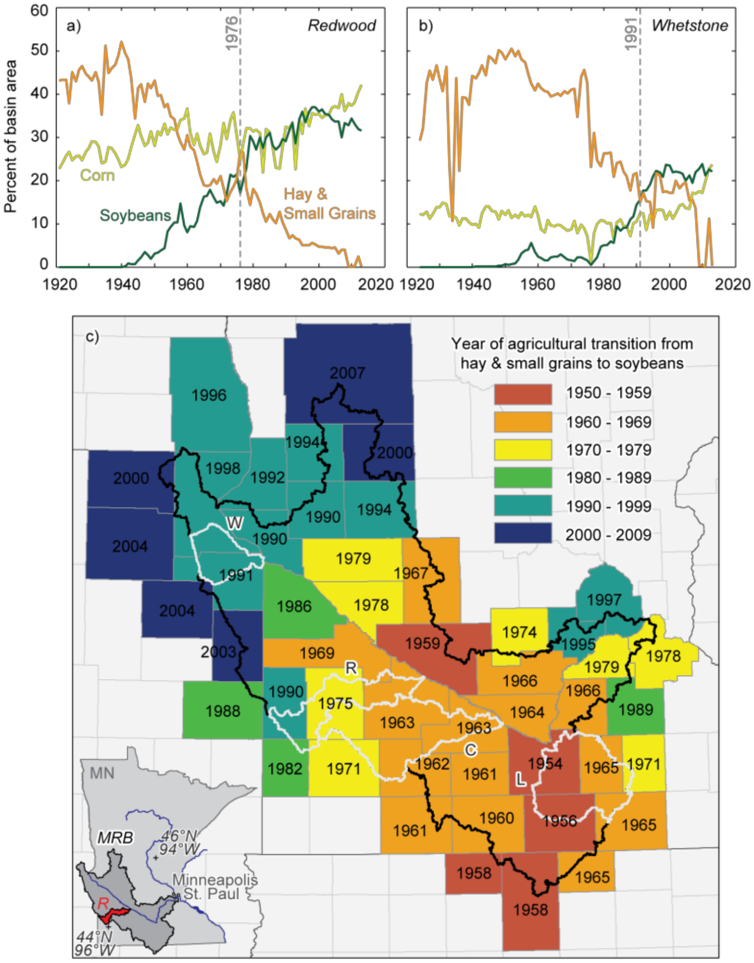
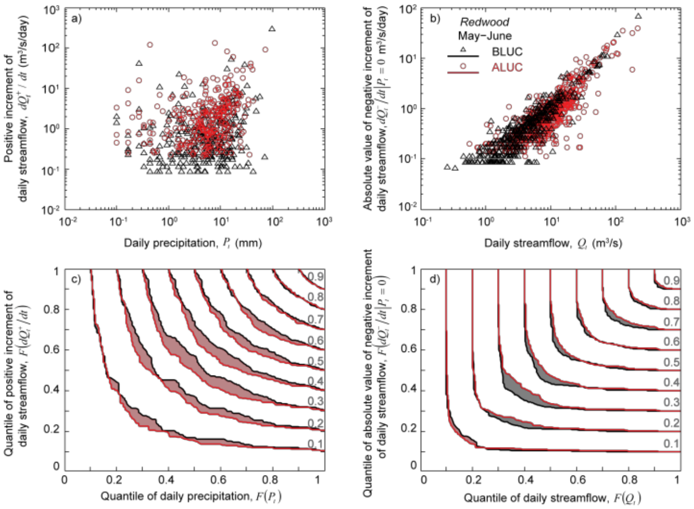


Figure 3. Temporal progression of agricultural changes in the MRB. The agricultural transition year is defined as the year when the percentage of the basin area for growing soybeans exceeded that for hay and small grains (barley, flax, oats, rye, and wheat) (see examples in (a) and (b) for the Redwood and Whetstone basins). The map of (c) demonstrates the southeastern to northwestern progression of this agricultural transition. The Redwood (R), Whetstone (W), Cottonwood (C), and Le Sueur (L) sub-basins are shown for reference.

Figure 4. Copula inter-quantile analysis of hydrologic response for the Before Land-Use Change (BLUC; black) and After LUC (ALUC; red) periods of the Redwood basin (where 1976 separates the two periods for analysis, see Fig. 3). (a) Scatterplot of positive slopes of daily hydrographs dQ_t^+/dt versus previous day precipitation P_t. (b) Scatterplot of negative slopes of daily hydrographs dQ_t^-/dt conditioned on no previous-day rainfall ($P_t = 0$) versus streamflow Q_t. (c) Copula of dQ_t^+/dt and P_t. (d) Copula of $dQ_t^-/dt\ |P_t = 0$ and Q_t. A strengthened dependence of streamflow increase to previous day rain (plots (a) and (c)) and a reduced dependence of the falling hydrograph slope to streamflow magnitude (plots (b) and (d)) is observed in the ALUC period.



3. Expression of Geologic Controls on Multi-Scale River Network Structure

External climatic or geologic controls, such as tectonics or glacial drainage, might impose constraints on landscape self-organization resulting in spatial patterns of rivers and valleys which do not obey the typical self-similar or self-affine relationships found in most landscapes. We have quantified how such geologic constraints might express themselves on channel network topology, spatial heterogeneity of drainage patterns, and emergence of preferred scales of landscape dissection. We used as an example the Headwaters River basin located in the upper MRB where successive glaciations have carved the landscape that has evolved over the past thousand years leading to a pronounced spatially anisotropic channel network structure which violates most scaling laws of fluvial landscapes [*Danesh-Yazdi et al., in preparation*]. Figure 5 illustrates the MRB and the geological feature called Coteau des Prairies (CDP) which was formed around 100,000-10,000 BP as a result of repeated glacial cycles covering the bedrock with glacial till deposits. It is seen how the channel dissection of those MRB sub-basins containing the CDP region differs drastically from the drainage pattern of typical landscapes, with persistence of quasi-periodic ridges and valleys and high channel density.

We found that typical Hortonian self-similarity tests are unable to detect the spatial heterogeneity in topology, while the stricter Tokunaga self-similarity test can reveal the irregularities present in the branching structure of these river networks. The length-area scaling and the probabilistic relationship between the slope and local drainage density also revealed how geologic constraints created a competition for space resulting in channel geometric and topographic properties different from those expected in typical landscapes. To identify the specific preferred scales of organization in such a landscape, multi-scale detrending via wavelets was used to successively remove scales of interest and examine how the variance of the detrended landscapes changed with scale. The analysis revealed a spectral gap at scales corresponding to the wavelengths of the quasi-periodic ridges and valleys present in CDP region (Fig. 6). *The ultimate scope of our study is to investigate how the multi-scale variability in landscapes depicts pronounced regularities (probably the result of an externally imposed control such as geology) that "break" away from the typical "cascade of energy" so familiar for landscapes that have evolved in the absence of external controls. The range of scales of this externally imposed "regularity" is then quantified and descriptions of the self-dissimilar network structures investigated to aid in the quantitative analysis of how fluxes in the basin depend on scale*.

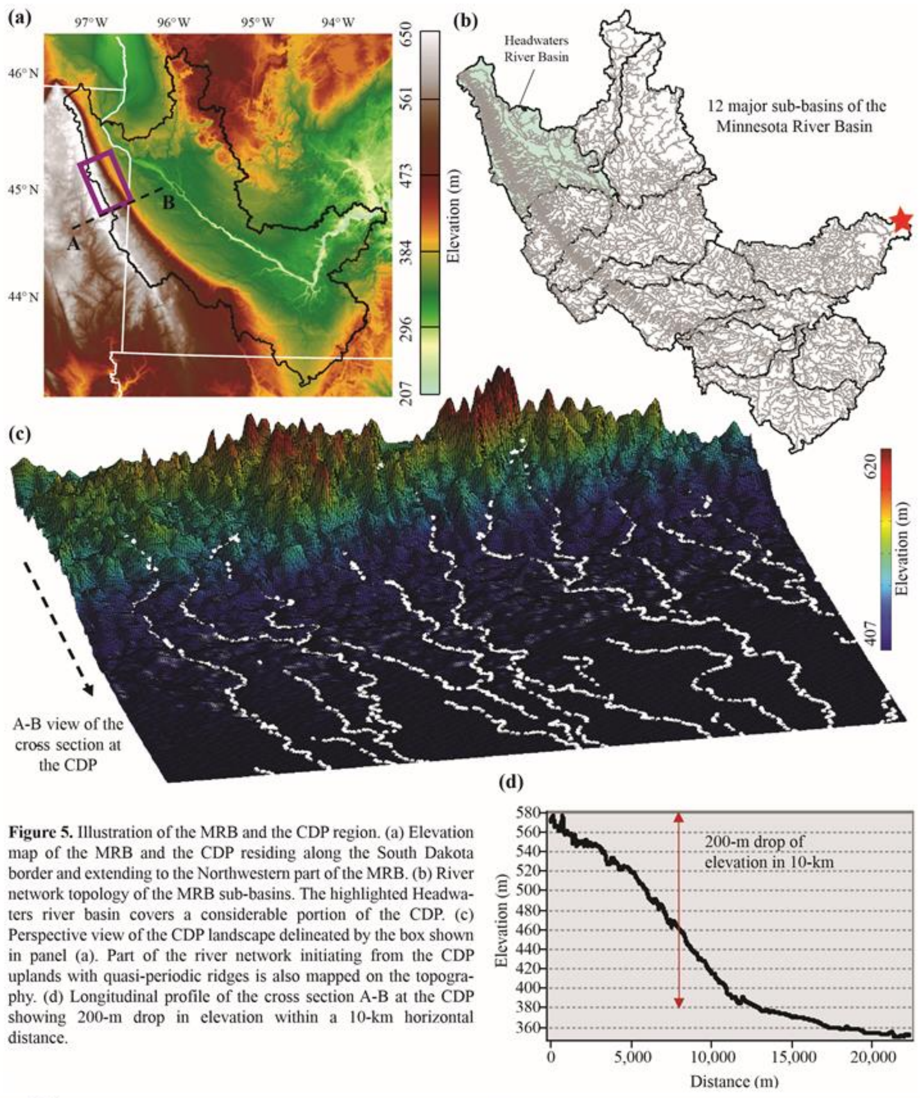


Figure 5. Illustration of the MRB and the CDP region. (a) Elevation map of the MRB and the CDP residing along the South Dakota border and extending to the Northwestern part of the MRB. (b) River network topology of the MRB sub-basins. The highlighted Headwaters river basin covers a considerable portion of the CDP. (c) Perspective view of the CDP landscape delineated by the box shown in panel (a). Part of the river network initiating from the CDP uplands with quasi-periodic ridges is also mapped on the topography. (d) Longitudinal profile of the cross section A-B at the CDP showing 200-m drop in elevation within a 10-km horizontal distance.

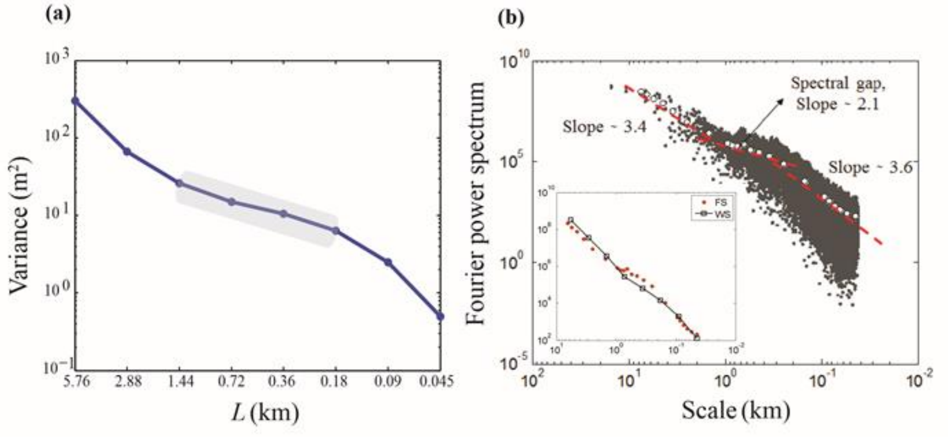


Figure 6. (a) Variance of the detrended landscape containing features smaller than L versus scale L. A reduced contribution to the overall variance is observed from features within scales of 0.18 km-1.44 km. (b) The Fourier and wavelet (indicated as inset) power spectra for the original landscape residing within the CDP region. The spectrum shows a spectral gap between scales ~ 0.3 km–1.5 km, which are close to the wavelengths of the quasi-periodic ridges and valleys present in this region as instigated by the large-scale geologic control of 14,000 years ago.

4. Meandering River Dynamics

Meandering rivers with high rates of channel migration can deliver large quantities of sediment to rivers, indirectly affect water quality and biotic functioning, and increase the risk to public and private property. In order to understand how, and ultimately predict where, a river channel will migrate, the challenge lies in linking the meander process to the sinuous river channel planform pattern. To this end we used numerical modeling to establish links between a meandering river's planform (i.e. shape) and its migration dynamics [*Schwenk et al*., 2015]. We found that the physically-based yet simplified model dynamics inherently produce a prototypical bend shape, dubbed *simple*. Cutoffs act as perturbations to the channel planform, resulting in a spectrum of bend geometries including two other archetypal geometries: *round* and *long* (Fig. 7b). Using three measures of bend migration, we showed that bends with similar cutoff geometries shared similar dynamic histories, enabling the inference of historic dynamics from static cutoff shapes. Specifically, *simples* migrated fastest and *longs* slowest with *rounds* showing significant variability in their dynamic trajectories.

Results of this work have both practical and theoretical implications. Inferring channel dynamics from static planform shapes is vital to understanding a river's dynamic past, especially in cases where no historic data are available, and aids in stratigraphic interpretation. If the Mississippi River in Minnesota were reasonably well-described by our model, aspects of its morphologic history could be estimated despite a lack of historic data through simple measurements of oxbow geometry (Fig. 8a). Furthermore, our analyses indicated that individual meander bends were most sensitive to perturbations early in their lives. This result may aid decision makers when considering dam and bridge constructions, dredging, and bank armoring.

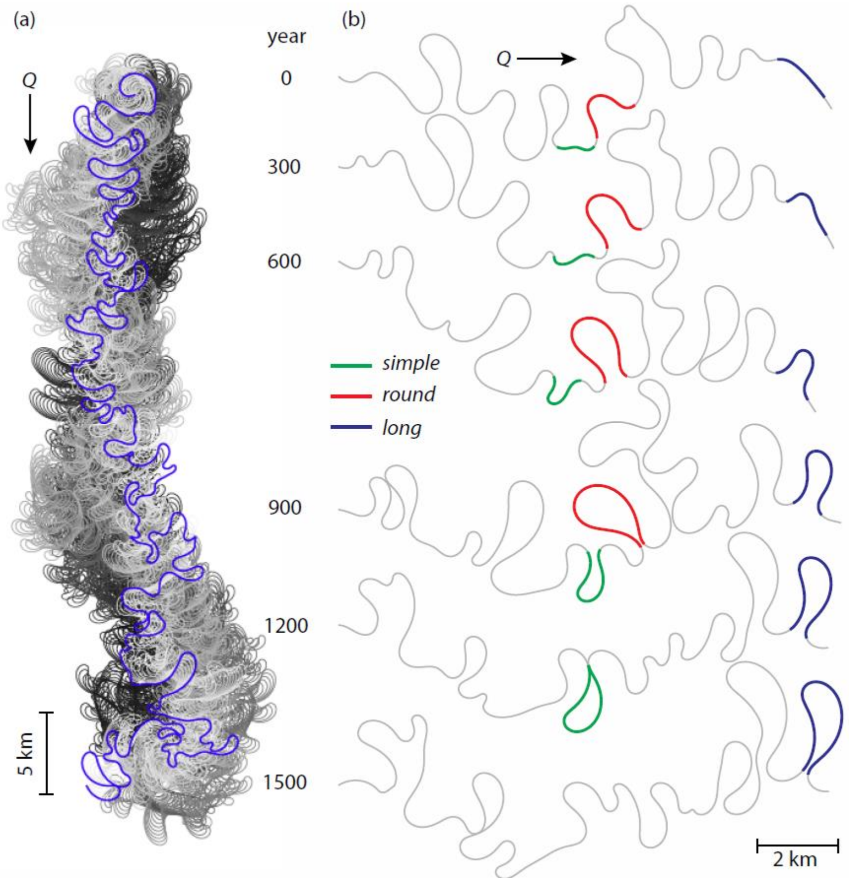


Figure 7. A long-term simulated meandering river. (a) 30,000 years of modeled centerline realizations. Older centerlines are darker; the blue centerline shows t = 30,000 years. The upstream boundary condition fixes the first centerline node in place, leading to the formation of the spiral pattern at the upstream boundary. No restrictions are placed on the downstream node so the river may migrate freely. (b) A reach of simulated centerline selected shows the growth and cutoff of three prototypical bend types that emerge from the physically-based deterministic model dynamics. Realizations are 300 years apart. Note the complex multilobe meander that starts as double lobed but develops a third lobe before cutting off between 900 and 1200 years.

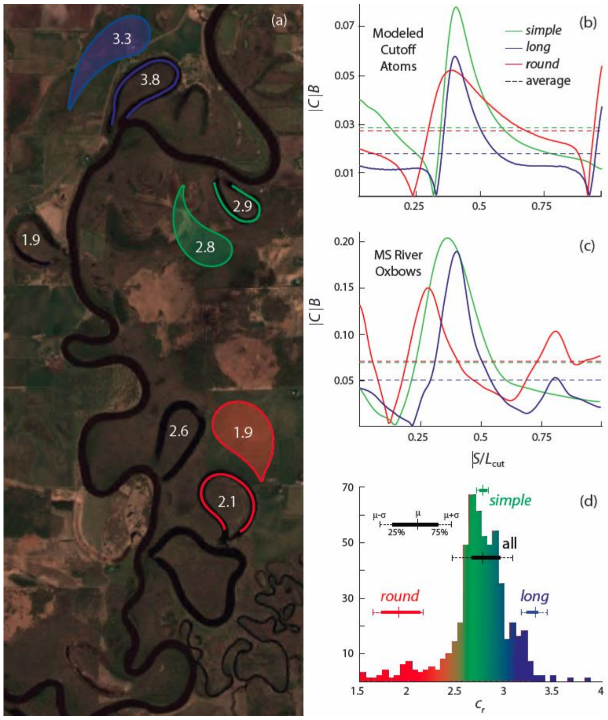


Figure 8. Geometric classification via curvature measures for modeled and real meander loops. (a) Aerial photo of a reach of the Mississippi River in Minnesota, USA. Centerlines of three oxbows have been traced in colors corresponding to the cutoff bend geometry they most resemble. The shaded meander loops are cutoff bends simulated by the model and are positioned next to similarly shaped oxbows. White numbers in the center of each oxbow or model bend are c_r values (ratio of apex curvature to average curvature). (b) Absolute value of curvature signals for the cutoff bends simulated by the model shown in (a). Dashed lines are average absolute curvatures. (b) Absolute value of curvature signals for the traced oxbow lakes of the Mississippi River shown in (a). (c) The distribution of c_r simulated by the model shows how c_r serves as a good metric for ordering meander loops of various geometries by shape. The color gradient of the c_r histogram emphasizes that simulated bend shapes are characterized by a spectrum rather than falling neatly into one of the three archetypal shape (*simple, round, long*) categories. Statistics for each group have sample size n=25, while n=552 for all cutoff bends. The c_r mean value for all cutoff bends is 2.77. Map data: *Google Earth: DigitalGlobe*. 46◦37’31.36”N, 93◦38’13.31”W. Imagery date 7/2/2011.

5. Integrative Hydro-Geo-Biological Predictive Modeling

Freshwater fauna have dramatically declined in both diversity and abundance worldwide concurrent with changes in streamflow and sediment loads in rivers. To understand how cumulative effects and interdependency of chronic environmental stressors, e.g. high suspended sediment concentrations and phytoplankton (food) limitations, may affect population dynamics of long lived organisms, such as freshwater mussels, a simplified dynamic interaction model that couples hydrology to river ecology (Fig. 9) was developed [*Hansen et al*., 2015]. Using this model we demonstrated how the observed hydrologic change and/or the water-driven sediment generation dynamics may modulate a regime shift in river ecology, namely extirpation of native mussel populations, at several sites in the MRB [*Foufoula-Georgiou et al*., 2015]. Such analysis can be useful in guiding possible remediation strategies, as briefly illustrated below.

Observed mussel population density at the Redwood site is among the lowest in the MRB (Fig. 9c). We simulated mussel population densities across a range of realistic sediment generation (α,β values in Fig. 9b) using repeated Before Land-Use Change (BLUC) or After LUC (ALUC) (see Fig. 3) streamflows until populations reached a steady state (Fig. 10a). The resulting α,β space can then be divided by a line demarcating the critical threshold for a regime transition that is determined by the applied hydrology; above this line, populations are extirpated and below this line, populations reach their effective carrying capacity. This space for the Redwood site (Figure 10b) tells a compelling story. Conservatively consider that sediment generation has remained constant across both BLUC and ALUC periods (gray “+” symbol). In this case, altered hydrology via streamflow alone was sufficient to switch the population to extirpation. If, on the other hand, sediment generation did change along with hydrology (black triangle for BLUC, red circle for ALUC), the respective α,β are farther from the regime transition line in both BLUC and ALUC periods, indicating an even more drastic change in the rate at which the populations approach steady state. In either case of altered hydrology or altered sediment production, a population growing toward its effective carrying capacity in BLUC conditions declines toward extirpation under ALUC conditions.

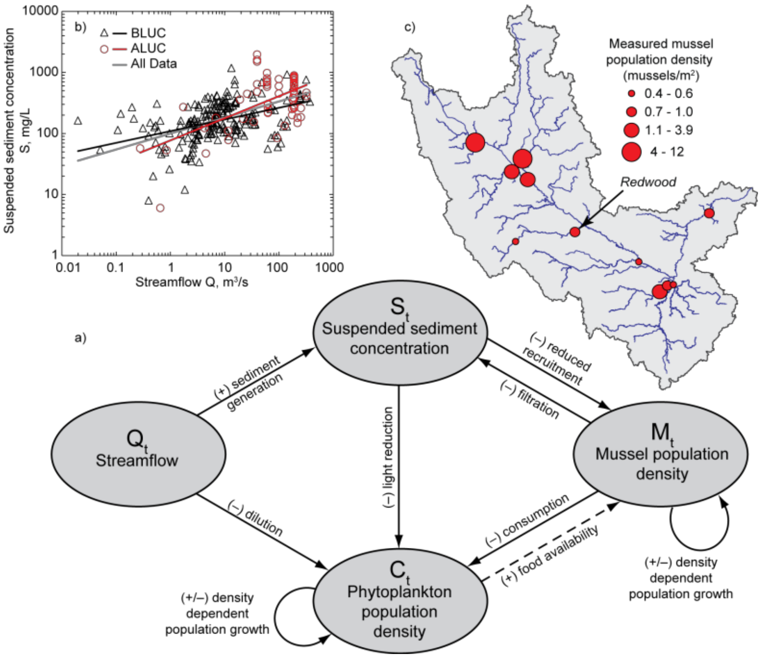
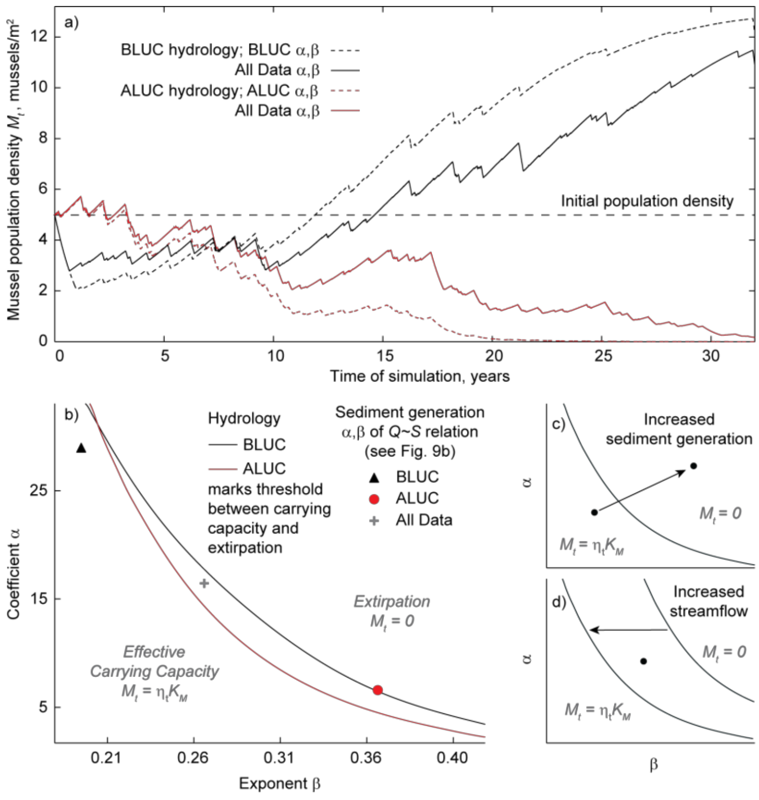


Figure 9. Overview of simulated mussel population dynamics driven by streamflow. (a) Schematic of the process interaction network showing the couplings incorporated in the mussel population density model. Each arrow represents a physical interaction considered by the model which is either positive (+) or negative (-). (b) Flow-sediment relationship from USGS gaging station data with power law fits for BLUC (n=207), ALUC (n=67), and all data. *α, β* values for each period: BLUC (29.1, 0.191), ALUC (6.36, 0.362), and all data (16.4, 0.262). (c) Map of the Minnesota River basin showing the sites (red circles) with observed mussel population densities where the model of *Hansen et al*. [2015] was applied. A detailed analysis of model dynamics focuses on the Redwood site indicated by the arrow.

Figure 10. Mussel population stability as a function of hydrology and sediment generation. (a) Mussel population densities are simulated for 32 years driven by hydrology Before Land Use Change (BLUC; black lines) and After LUC (ALUC; red lines) (see related Fig. 3 and 4). For each hydrology, populations were simulated using the flow-sediment relationship of the respective period (dashed lines) and the relationship derived from the entire record (solid lines). (b) Population stability diagram for the Redwood site. Regime transition lines depend on observed hydrology, while positioning in the space depends on the (*α,β*) fits to observed data (Fig. 9b). Points above a given line correspond to (*α,β*) pairs that result in extirpation as the stable fixed point, while those below have a stable fixed point at the effective carrying capacity. Points far away from the line reach steady state faster than those nearer the line (see (a)) (c) Fixed point stability may switch due to changes in sediment generation or (d) changes in hydrology.



Future Research (2015–2016)

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

1. Network Approach to River Basin Vulnerability Assessment.

- Relax some of the assumptions of the network-based sediment transport framework to include storage and space-time variable release of sediment in the system.
- Use this framework to investigate management actions and vulnerability/resilience questions to future changes in the MRB.
- Extend the network-based model to include water retention basins for modeling nutrient and fine sediment transport in a watershed to guide mitigation and planning strategies, i.e., where and with what properties to locate retention basins for achieving desired objectives.

2. Effect of Agricultural Drainage on Hydrologic Response

- Further quantify the effect of tile drainage on the basin hydrologic response at multiple temporal scales (daily up to weekly) by performing analysis of several sub-basins within the MRB and relating the results to land use change.
- Understand how the hydrologic response change depends on spatial scale (plot to large watershed scale) via coupling a response function model with a network transport model.
- Use a travel time distribution approach and available data of nutrients or other tracers to understand the storage function of the pre-development and post-development landscapes and assess whether such a systems level approach to watershed modeling can be useful for management and planning.

3. Expression of Geologic Controls on Multi-Scale River Network Structure

- Understand how river networks not obeying the typical self-similar structure can be modeled via extended forms of higher-order branching structure topologies.
- Investigate more closely the break of self-similarity and its physical causes in other sub-basins within the MRB.
- Explore how topologic self-dissimilarity projects itself into a break in the scaling of mean annual and maximum annual peak streamflows with upstream contributing area.

4. Meandering River Dynamics

- Test the connections found between simulated planform geometries and migration dynamics using real data from Landsat imagery – for this, one of the most rapidly migrating rivers of the world (Ucayali River in Peru) has been selected for analysis.
- Further understand how natural meander migration is affected by constraints imposed by human factors and how these external perturbations propagate throughout the system to change the dynamics of meander growth and cut-offs.
- Evaluate the performance of a suite of meander migration models of various complexities by comparing dynamic trajectories of real river bends.
- Probe the inherent nonlinear dynamics in meandering river planforms and dynamics using tools from nonlinear dynamical theory to better understand sensitivity to future perturbations.

5. Integrative Hydro-Geo-Biological Predictive Modeling

- Theoretically study the non-linear dynamics and threshold behavior (two states of attraction) of the developed hydrologic-ecologic model and understand what parameters or model component parameterizations mostly control the long-term behavior.
- Perform a more extensive sensitivity analysis to unknown or poorly estimated parameters to pinpoint what quantities need to be known in a basin to be able to accurately predict the water-sediment-mussel population density continuum.
- Use the model as a tool to suggest management scenarios in a basin that might allow declining mussel populations to rebound and avoid further decline toward an extinction threshold.

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Research update

Like many human dominated watersheds, excess sediment, nitrogen, phosphorus, and water are the major drivers of water quality degradation and biological impairment in the Minnesota River Basin (MRB). Impairment of MRB streams and lakes exceed that of many other Midwestern watersheds, and therefore serve as an important example of disproportionately large impacts of one watershed on regional water quality. The extreme conditions in the MRB arise from complex interactions of geological history, land use, and climate change. Our research assesses landscape and climate change drivers of stream biogeochemistry, biological structure, and ecosystem processes in agriculturally dominated watersheds studied in the REACH framework. We are using data synthesis, modeling, and GIS to identify controls of watershed nutrient export through leveraging analyses of existing databases. With new data collection efforts, we are examining relationships between river network physical structure and biological processes to inform predictive modeling of nutrient transport and cycling, and food web structure in highly dynamic landscapes. We focus intensively on understanding the influence of wetlands, lakes and riparian zones on local and downstream structure and processes in stream networks, and legacy nutrients. Research described below is in early to mid stages of implementation, with emphasis on activities from summer 2014. The empirical information we are generating and synthesizing from monitoring programs is gathered with a goal for integration and validation of several modeling efforts, many described elsewhere in this report.

1. Large Watershed Nutrient Mass Balance Analyses

We are analyzing annual watershed loading data and building nutrient mass balances to identify factors that lead to nutrient retention or stream losses in southern Minnesota (MN). We calculated nitrogen (N) retention for 57 watersheds in MN using estimates of Net Anthropogenic Nitrogen Inputs (NANI) and annual nutrient loads calculated by the Minnesota Pollution Control Agency and Metropolitan Council using methods described previously [*Howarth et al*., 1996; *Boyer et al*., 2002]. N retention includes N taken up on the landscape or denitrified into gaseous forms, and not released to streams and rivers. Annual loads for 2007-2011 were averaged, incorporating substantial variation in runoff. Sites spanned a gradient of urban, agricultural, forested, and wetland dominated land cover. Highly agricultural watersheds (>25% cropland) have high N inputs, but N retention is highly variable between sites. N retention decreases with greater N inputs (Fig. 11; n=39, R^2= 0.28, p<0.001). Greater runoff and average annual precipitation are associated with lower N retention and greater wetland and lake cover are associated with higher N retention. N retention at highly agricultural sites is best described with a multiple regression including precipitation, crop cover, and lake cover (n = 35, R^2 = 0.68, p<0.001). Thus, variation in precipitation and land use intensity are important to determining how much N is taken up or denitrified in watersheds. Additionally, lakes and wetlands in agricultural areas are important sinks for inorganic N.

Plans for next year: Net Anthropogenic Phosphorus Input (NAPI) calculations are ongoing and will be used with watershed phosphorus (P) loading data to analyze factors that regulate P retention across watersheds. Examination of interannual variability in N and P export driven by climate is planned using the multi watershed database described above, as well as analysis of the factors controlling the specific forms of N and P exported (i.e. organic vs. inorganic nitrogen, and dissolved vs. particulate P).

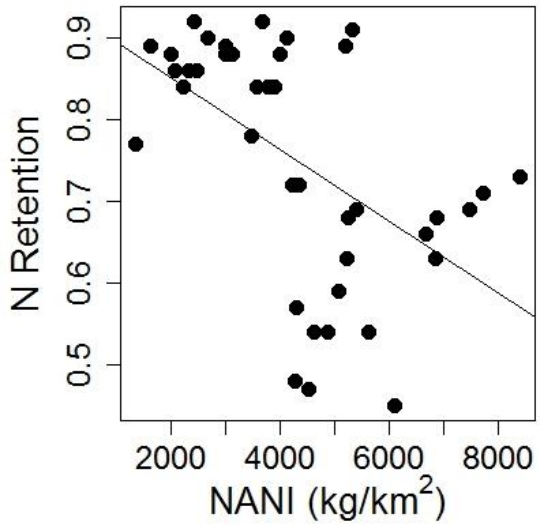


Figure 11. Annual watershed nitrogen (N) retention decreases with greater N inputs in highly agricultural watersheds. N loss to rivers (i.e. lower retention) under higher NANI conditions is related to higher watershed runoff, and lower losses (i.e. higher retention) is related to extensive coverage by lakes and wetlands, which serve as sinks for NO_3 leached from farm fields.

2. Sources, sinks, and controls of nitrogen and phosphorus in the Le Sueur River

The MRB is a major source of N and P to the Upper Mississippi River, and a relatively small part of the basin contributes the majority of nutrient loadings. The Le Sueur River watershed is representative of a “hotspot” for high nutrient export and poor water quality which impairs local and downstream biotic conditions and ecosystem services. This watershed is a focal area for much of our field research to understand sources and sinks for nutrients, and the interactions of climate and human actions that affect N and P.

Nitrogen: Stream nitrogen concentrations and loads peak during spring time conditions in the MRB, similar to other Midwestern watersheds. Record rainfall was observed during spring for much of MN during 2014. Despite the high water conditions, which can rapidly flush nutrients to large rivers without incorporation into plants, we observed signification retention of nitrogen in lakes and remnant wetlands. For example, across 94 sites sampled in one week in June and again in one week in August in three MRB HUC-8 basins dominated by crop cover with watershed areas ranging from 3 to 5,800 km^2 a significant negative relationship between nitrate concentration and percentage of drainage area that is wetlands or lakes was observed (Fig. 12). No relationship was seen between nitrate concentration and drainage area. Sampling through time at ten sites with drainage areas ranging from 0.5 to 20 km^2 and a range in extent of wetland cover showed that remaining wetlands suppress current N losses in the spring time period (Fig. 12). In addition to providing strong sinks for NO_3, lakes and remnant wetlands also increase levels of dissolved organic carbon (DOC) in stream water, which may enhance denitrification downstream (Fig. 13). These data suggest that small to modest increases in wetland cover could have strong positive impacts on N retention.

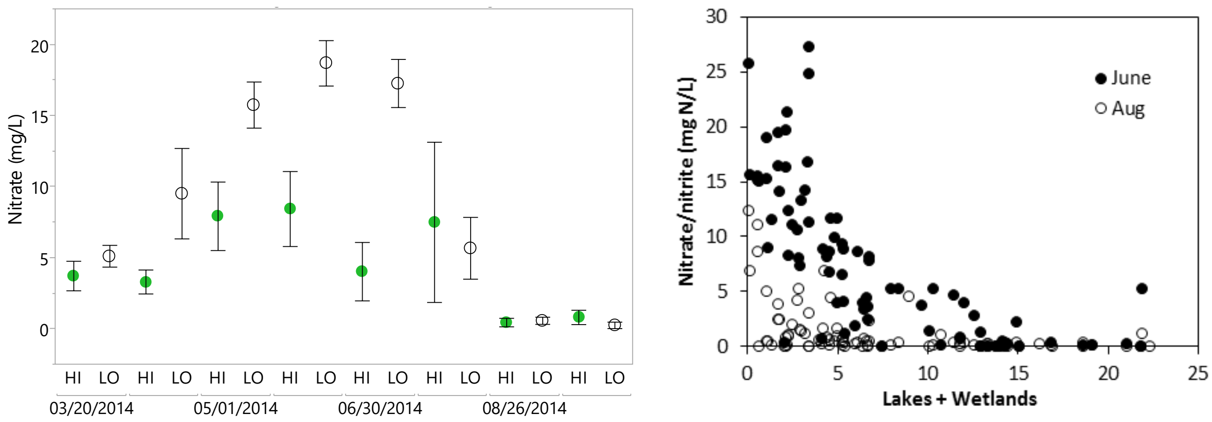


Figure 12. Temporal (left) and spatial (right) patterns of stream water nitrate/nitrite concentrations as measured in the Minnesota River Basin in 2014. Upstream wetlands and lakes decrease nitrate concentrations in receiving agricultural ditches during the critical spring loading period of April – June. Green closed circles are mean concentrations in ditches with > 5% wetland or lake coverage of their drainage area and open circles represent sites with < 5% wetland or lake coverage. Figure on right shows nitrate concentrations measured at ~90 locations in 3 sub-basins of the MRB at two time periods; one in June and one in August.

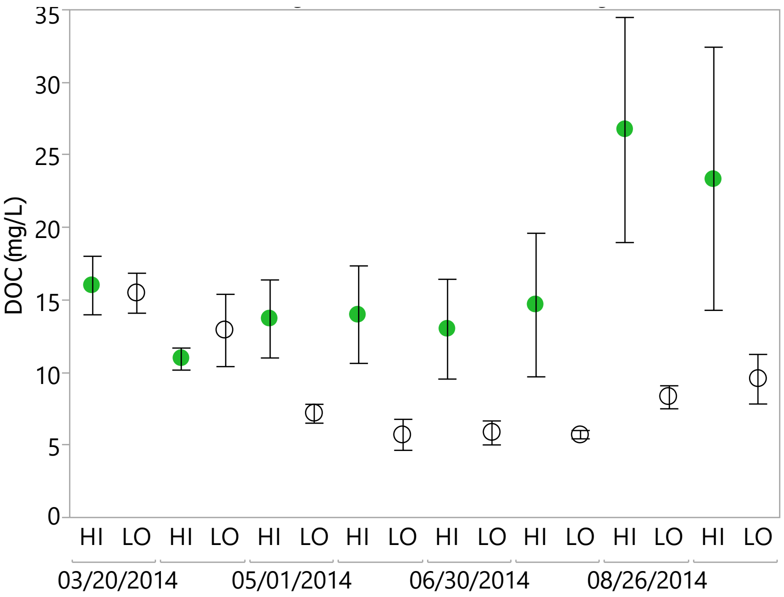


Figure 13. Upstream wetlands and lakes enhance the availability of carbon, in the form of DOC in agricultural ditches during most of the growing season. In early spring (March and April) ditch DOC is relatively high regardless of the presence of wetlands. Green closed circles are mean concentrations in ditches with > 5% wetland or lake coverage of their drainage area and open circles represent sites with < 5% wetland or lake coverage. Each point is the mean concentration for 5 locations. Errors bar represents one standard error from the mean.

Phosphorus: Excess phosphorus in streams, lakes, and rivers causes widespread impairment of water quality and habitat for biota throughout Minnesota, and much of the Midwest. While progress has been made in reducing P losses from sewage and field erosion sources, many waterways remain highly eutrophic. We are using intensive sampling and modeling to understand the source of P losses from the Le Sueur Basin toward identification of strategies that will be most efficient and effective for improving P retention. This work was not originally proposed and is leveraged via new funding from the Minnesota Department of Agriculture (MDA). Intensive sampling of the Le Sueur and two other agricultural watersheds, combined with analyses of state datasets (see previous section) show that soluble P dominates the total P concentrations and annual loads at a majority of sites. Soluble and particulate P appears to have different sources in the landscape. Soluble P levels often peak at snowmelt, but remain elevated throughout many agricultural drainage networks throughout the year. Particulate P levels are closely related to total suspended solids (TSS) concentrations, and have two major sources: lakes and bank erosion. Lakes strongly increase particulate P, reducing soluble P levels, and often function as hotspots for total P transport into rivers. Erosion of stream banks and bluffs is also an import source of particulate P in some watersheds, including our focal study sites in the Greater Blue Earth River Watershed. Ongoing work will relate sediment budgets developed within this and related projects to P budgets. Several modeling approaches, including SWAT, will be compared toward an integrated understanding all P sources and environmental controls in order to develop strategies for phosphorus management.

3. Patterns and processes effecting biotic structure in agricultural drainage networks.

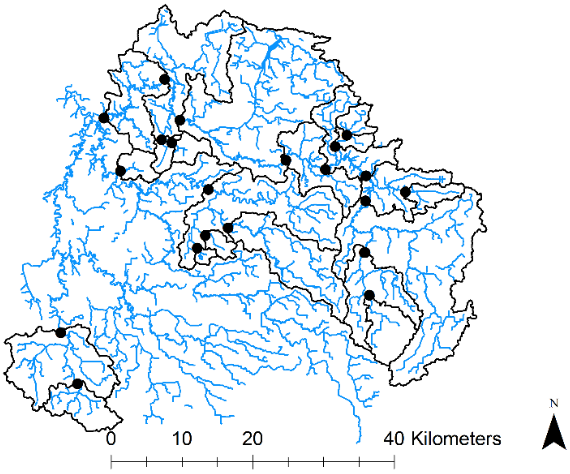
A holistic management approach to water quality challenges in the MRB depends on eliciting the linkages between physical processes, such as hydrology and sediment transport, and biological processes, such as the structure and function of river food webs and the sources of carbon that support them. Organic matter dynamics in streams and rivers – i.e., inputs, local production, storage, assimilation, and transport – are governed by flow conditions and related drivers, including climate, geology, and human land use [*Humphries et al*., 2014]. During times of rising flows, for example, rivers are often characterized by the longitudinal transport of material and energy from upstream allochthonous sources; at low flow conditions, by contrast, local autochthonous and local allochthonous inputs are thought to predominate [*Humphries et al*., 2014]. These variations in organic matter inputs and transport likely have important consequences for ecosystem processes and biota. Indeed, patterns in the variability and predictability of flow conditions and organic matter availability acting over very long time scales may represent strong evolutionary forces that shape life history strategies of many types of aquatic life, including plants, aquatic insects, and fish [e.g., *Winemiller and Rose,* 1992].

Filter-feeding and collecting macroinvertebrates are two groups of stream biota that feed on suspended and deposited particulate organic matter, respectively [*Wallace and Webster*, 1996]. The growth of these groups may therefore reflect dynamics in organic matter production, storage, and transport that stem from hydrogeologic drivers. For example, depending on ambient conditions and the specific taxa in question, filter feeding invertebrates may rely on suspended particulate organic matter (POM) from a number of different sources, including instream primary production (e.g., phytoplankton), processed allochthonous inputs from riparian vegetation or watershed sources (i.e., leaf litter), mobilization and transport of benthic organic matter, or soil organic matter washed from stream banks or watershed sources [*Wallace and Webster*, 1996; *Sheih*, 2002]. The growth and production of these feeding groups may subsequently propagate throughout river food webs, by affecting the quantity and type of POM in suspension, or by altering the structure of local benthic communities [*Wallace and Webster*, 1996].

Primary water quality concerns stemming from the intersection of human- and climate driven change in the MRB are excess sediment and nutrients [*MPCA*, 2015]. Suspended sediments are often considered detrimental to instream primary production, as sediments can both block light penetration to the stream and physically abrade instream macrophytes and algae [*Wood and Armitage*, 1997; *Henley et al*., 2000]. At the same time, however, excess nutrient levels in streams and rivers of the MRB can result in high levels of algal production at low flows. Thus, the nature of the relationship between suspended sediments, nutrients, and the production and transport of organic matter that represent potential food resources for macroinvertebrates is complex.

With this research, we are investigating variability in biodiversity, food sources and food web structure across stream networks, from upstream drainage ditches to downstream rivers, and across seasonal differences in flow, water chemistry, organic matter availability, and suspended sediments. Macroinvertebrate, water chemistry, and organic matter samples collected from the Le Sueur River basin in 2013 and 2014, together with additional prospective data to be collected in 2015 (Fig. 14), is being analyzed to address a number of hypotheses related to this objective.

Figure 14. Study sites and contributing watersheds in the Le Sueur River basin from which macroinvertebrates and sources of organic matter were collected for stable isotope analysis.



For example, we hypothesize that, in spring and early summer, filter feeders will consume fine particulate matter derived from benthic or soil stores, but will increasingly rely on organic matter derived from planktonic algae as the summer season progresses. Preliminary data from the Le Sueur River basin indicates that suspended POM in spring and early summer may derive from multiple sources, including soil organic matter, whereas POM in late summer is derived largely from instream primary production throughout the stream network (Fig. 15).

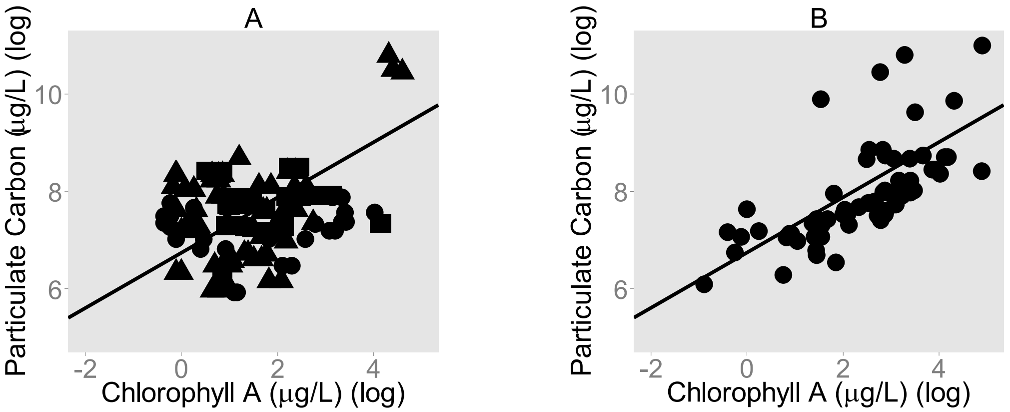


Figure 15. Particulate organic carbon as a function of chlorophyll concentrations in the Le Sueur River basin, in a) May-July, and b) August. Symbols indicate month of sample collection: cross=May, square=June, triangle=July, circle=August. The lack of relationship between chlorophyll and POC in May-July suggests that suspended carbon may derive from multiple sources in early- to mid-summer. The correlation between chlorophyll and POC in August indicates that suspended organic matter is largely derived from sources of instream primary production – i.e., phytoplankton-- in late summer (i.e., at lower flows).

A second aspect of this research is to couple an understanding of N and P sources and sinks (from Objective 2 above) to patterns in fish and macroinvertebrate biodiversity. This effort will leverage extensive biomonitoring datasets collected by MPCA and MN DNR to understand how landscape influences such as wetland cover may mediate relationships between stressors, such as excess nitrogen, and stream and river biodiversity.

Finally, we have sought to leverage the interdisciplinary partnerships fostered within the REACH group by proposing additional research, prospectively funded by the U.S. Environmental Protection Agency, which would integrate hydrological, ecological, and economic models at common spatial and temporal scales to understand the economic benefits of nutrient management conservation scenarios in the Upper Mississippi River basin (including the MRB). Designed in collaboration with Dr. Cathy Kling (another REACH PI) from Iowa State University, the objectives of this proposed research are to, 1) develop statistical ecological models to forecast the effects of watershed-scale conservation practices on the distribution of biodiversity (fish and aquatic insects) in streams and rivers of the Upper Mississippi River Basin (UMRB); 2) translate changes in biodiversity into ecosystem goods and services, and quantify their economic value using state-of-the-art revealed preference surveys and field experiments conducted with residents from a wide range of ecological and socio-economic conditions in the UMRB.

4. Watershed Scale Hydrologic Modeling

Efforts linked to watershed scale modeling of the Minnesota River Basin have focused primarily on improving the quality of the precipitation input data that have been used to inform the model. Previous model precipitation inputs have been based on either (1) volunteer observer stations, or (2) the Climate Forecast System Reanalysis (CFSR) data from the National Centers for Environmental Prediction. The CFSR data are generally an improvement over the volunteer observer stations because they provide uniform spatial coverage with no data gaps. However, with a grid resolution of approximately 38 km, the CFSR data may still be too coarse to capture intense but localized convective thunderstorms that are common during the summer in the upper Midwestern U.S.

More recently, precipitation data sets derived from NEXRAD radar data have presented another option for generating model inputs. These data are available from 2002 onward and offer near-continuous spatial coverage for the continental U.S. The data are not available in a format that is easily prepared for use by the SWAT model and require additional processing to identify missing data and fill in gaps from nearby grid points via interpolation. However, the final data product is a virtual network of rain gauges with a 4 km grid resolution. SWAT model weather inputs now rely on NEXRAD for precipitation and CFSR data for remaining inputs (temperature, solar radiation, relative humidity, wind speed). These inputs have improved model performance (Fig. 16), and preliminary calibration results show good agreement for key tributaries of the Minnesota River Basin. Ongoing calibration efforts are currently focused on improving flow agreement during the receding hydrograph limb of flow events.

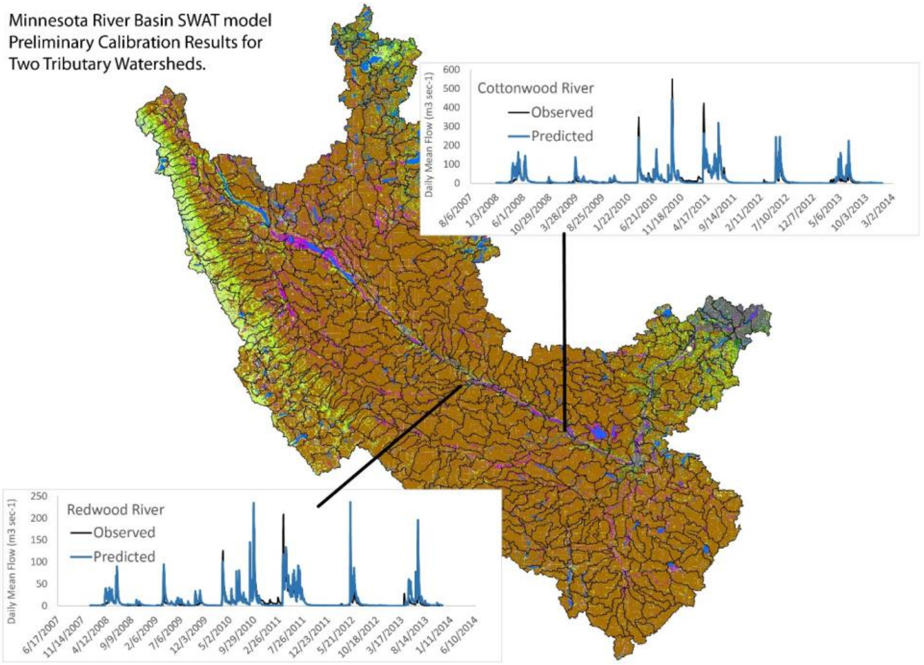


Figure 16. Preliminary hydrology calibration results from the SWAT model for the Cottonwood River Basin (3,367 km^2) and the Redwood River Basin (1,629 km^2).

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Karen Gran's group:

Martin Bevis, Nate Mitchell, Courtney Targos, Laura Triplett, and Virginia Batts

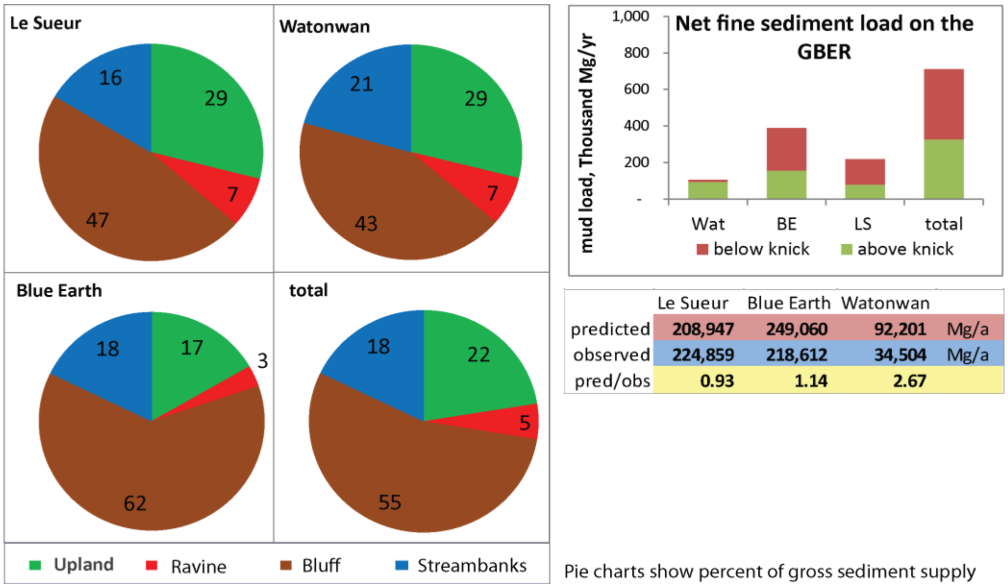
1. Understanding Sediment Sources in the Greater Blue Earth River Basin

Students: Martin Bevis (M.S. UMD 2015)

Main Collaborators: Peter Wilcock (USU), Patrick Belmont (USU), Stephanie Day (NDSU)

As a system under stress for high suspended sediment loads, there is a desire to understand sediment sources, pathways, and depositional sinks in the Minnesota River basin as well as develop an understanding of how the underlying geology and geomorphic history affect suspended sediment loading. We completed suspended sediment budgets for the Blue Earth and Watonwan Rivers in 2014, expanding upon a sediment budget already completed in the Le Sueur. Together, these budgets yield insights into how geology affects erosion and sediment loading in the Greater Blue Earth River basin.

About half of the GBER fine sediment load is sourced below knickpoints, a result of late Pleistocene base level fall. In the watershed as a whole, over half of the fine sediment load is eroded from bluffs (Fig. 17). Below knickpoints, 85% of eroded fine sediment is bluff-derived. Bluff frequency (bluff surface area per square kilometer of land surface) and linear erosion rate increase downstream below knickpoints. The highest channel width-normalized migration rates are found in alluvial channel reaches with high bedload supply, while bedrock slows bluff erosion rates (Fig. 18). Because bluffs are such large sources of suspended sediment, budget accuracy depends on accurately delineating bluff extents. The suspended sediment budgets for each tributary were compared with TSS gaging records from the last decade to assess accuracy. The budget overpredicts sediment loading in the Watonwan, the basin farthest to the west (and thus the driest basin). We are still awaiting sediment fingerprinting data to better constrain upland sediment yields from this basin.



	Le Sueur	Blue Earth	Watonwan	
predicted	208,947	249,060	92,201	Mg/a
observed	224,859	218,612	34,504	Mg/a
pred/obs	0.93	1.14	2.67	

Pie charts show percent of gross sediment supply

Figure 27. GBER suspended sediment budgets. Bluffs are primary sediment sources. About half of the sediment load is sourced below knickpoints [*Bevis*, 2015].

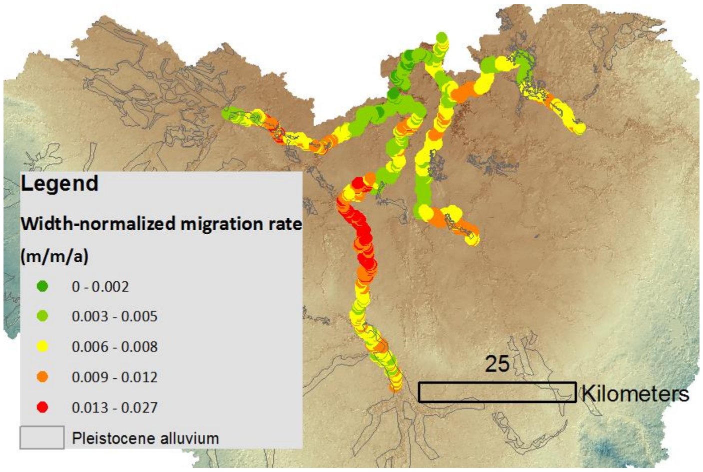


Figure 18. Greater Blue Earth River channel migration rates are highest where sources of bedload are abundant and lowest in bedrock reaches [*Bevis*, 2015].

The completed sediment budget including the spatial location and magnitude of different near-channel sediment sources (bluff, bank, and ravine contributions) are now being combined with a network routing model developed by *Czuba and Foufoula-Georgiou* [2014, 2015].

2. Effectiveness of Wetland Restoration on Reducing Peak Flows and Sediment Loading

Students: Nate Mitchell (M.S. UMD expected July 2015)

Main Collaborators: Se Jong Cho (JHU), Peter Wilcock (USU), Brent Dalzell (UMN), Karthik Kumaraswamy (USU), Patrick Belmont (USU), Ben Hobbs (JHU)

Following on the sediment budget research, we are working with a group of stakeholders to develop a consensus strategy to reduce fine sediment loads in the Greater Blue Earth River basin. Sediment loads, as measured by deposition rates in Lake Pepin, have increased more than an order of magnitude since the early 1800s [*Engstrom et al*., 2009]. Our sediment budget shows that most of this sediment comes from bank and bluff erosion [*Belmont et al*., 2011; *Day et al*., 2013; *Bevis*, 2015]. Along with the increase in sediment load, there has been a commensurate increase in peak flows [*Novotny and Stefan*, 2006; *Schottler et al*., 2014]. This work focuses on assessing the potential impact of wetland restoration on peak flow reduction and the resulting impact on sediment loading from near-channel sources.

For this, we utilized both the Soil and Water Assessment Tool (SWAT), a watershed-scale hydrologic model, and an empirical relationship between discharges in the lower watershed and sediment loading rates developed by colleagues at John Hopkins University (Cho and Wilcock, also part of the REACH project). Results for a wide range of scenarios (e.g., Fig. 19) have shown that hydraulic conductivity is one of the main limiting factors in peak flow and sediment loading rate reductions offered by wetland restoration. High hydraulic conductivities allow for increased seepage in wetlands, reducing peak flow rates in channels more than wetlands with low hydraulic conductivities. The identification of relationships between wetland surface areas and contributing areas as well as between peak flows and wetland extent has allowed us to create a reduced complexity model that can generate results for arbitrary wetland restoration scenarios. With this new model, one can select different wetland placement scenarios, design depths, and hydraulic conductivities, and quickly generate results on both peak flow and sediment load reductions. This new model runs in an Excel file and is intended for use by researchers and regional stakeholders to run scenarios in real-time to help develop a consensus strategy for sediment source reduction in the Greater Blue Earth River basin. The results generated from the simplified model are relatively similar to those obtained directly from SWAT output (Fig. 20).

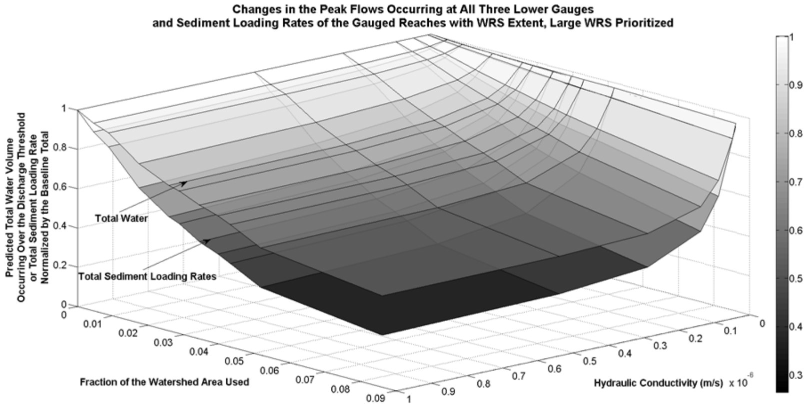


Figure 19. Projected changes in peak flows occurring at the lower gauges and sediment loading rates of the gauged reaches for water retention site (WRS) implementation scenarios prioritizing large wetland sites. Reductions increase non-linearly with the hydraulic conductivity of the sites' bottoms (K) at low K values, but level off as K increases [from *Mitchell et al*., in prep.].

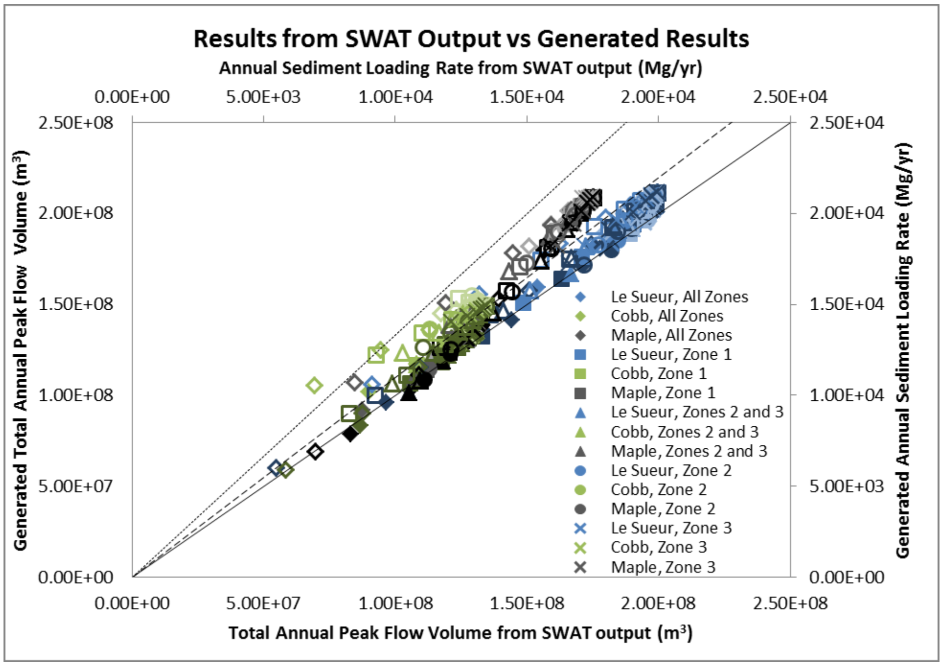


Figure 20. Total volumes of peak flows exceeding the threshold (0.01 $m^3/s/kms^2$) at the three lower gauges and sediment loading rates for the three gauged reaches derived from both SWAT output and generated values. Design depths of 1m, hydraulic conductivity (K) values of 1E-8, 1E-7, and 1E-6 m/s, and all placement zones are used. Symbols for K values of 1E-8 m/s use symbols with lighter shades (blue, green, and grey to black for the Le Sueur, Cobb, and Maple, respectively), symbols for K = 1E-7 m/s use intermediate shades, and symbols for K = 1E-8 m/s use darker shades. The symbols for K = 1E-7 m/s are shown in the legend. Filled symbols designate peak flow volumes, while hollow symbols designate sediment loading rate values. The symbols for zone 3 are an exception to this rule, however, as thick x's represent water volumes for zone 3, while thin x's represent sediment loading rates for zone 3. The solid black line indicates a 1:1 relationship between results from SWAT output and generated results while the dashed and dotted lines represent 1:1.1 and 1:1.33 relationships, respectively [from *Mitchell et al*., in prep.].

3. Holocene-Scale Adjustments to Channel Geometry and Discharge

Students: Courtney Targos (M.S. UMD expected July 2015)

Main Collaborators: Phil Larson (MNSU), Harry Jol (UW-EC)

Given evidence for strong channel adjustments (i.e. widening) over the past hundred years as discharges have increased [*Schottler et al*., 2014], we wanted to assess how channels responded to Holocene-scale changes in discharge. Did channels widen slowly through the Holocene as channel networks expanded, or are there strong variations in channel size due to climatic variations like the mid-Holocene dry period? To assess channel geometry and discharge from the time of deglaciation to the modern, we focused on the Le Sueur River, investigating meander cut-offs preserved on terraces.

Paleochannels, preserved on terraces via meander cutoffs during an incisional period, record the channel geometry and thus discharge throughout a river's history. We measured paleochannel geometry on terraces throughout the Le Sueur River in south-central Minnesota, to track how channel geometry has changed throughout the last 13,400 years. A rapid drop in base level 13,400 yr B.P. triggered knickpoint migration and valley incision that is ongoing today. Since the 1800's, the area has developed rapidly with an increase in agriculture and the amount of tile drainage, directly impacting river discharge by increasing water input to the river. Five paleochannels were identified on terraces along the Le Sueur River from 1m-resolution lidar data. Ground Penetrating Radar (GPR) was used to obtain a subsurface image across paleomeanders to estimate the geometry of paleochannels. By measuring the geometry of paleochannels, we can compare the channel geometry and effective discharge at the time the terrace was being carved to today's conditions. Three lines were run across each paleochannel perpendicular to the historic water flow. Each of the 15 lines were "processed" using the EKKO Project 2 software supplied by Sensors and Software to sharpen the images, making it easier to identify the paleochannel geometry. Paleodischarge was determined using the Law of the Wall and Manning's Equation. OSL samples were collected from overbank deposits to determine the time of channel abandonment. Paleodischarge coupled with depositional ages provide a history of flow conditions on the Le Sueur River.

Results show an increase in channel widths from the time paleochannels were occupied to modern channel dimensions from approximately 20 meters to 35 meters. The change was not constant through time, as all paleochannels analyzed on terraces had similar-sized channels. The best way to estimate paleogeometry was using the 'best interpretation' of GPR data, based on width-to-depth ratios; and paleodischarge was best estimated using Manning's equation with an n value of 0.035. Uncertainty estimates in paleogeometry can change paleodischarge calculations by 150%. Flood frequency analyses suggest a 1.5- and 2-year flood of 76 m3/s and 142 m3/s, respectively, which is comparable to estimations of bankfull based on current channel geometry, validating the methodology. Problems associated with paleogeometry estimations are primarily due to meander bend preservation in the subsurface, challenging GPR interpretation. The increase in channel geometry and discharge implies that the increase in agriculture and tile drainage since the area's development has greatly impacted the Le Sueur River resulting in a change in channel morphometry through increased erosion along the bluffs and banks. This increase in erosion has directly impacted the amount of sediment delivered to the rivers from banks and bluffs, increasing the turbidity in this turbidity-impaired river system.

4. Ecogeomorphic Response to Changing Flows

Students: Laura Triplett (M.S. UMN, 2015)

Virginia Batts (M.S. UMD, expected 2016)

Main Collaborators: Chris Lenhart (UMN)

Results from this study help to better understand and provide evidence for the relationships among vegetation establishment, hydrology, and sediment transport. Understanding these relationships and characteristics within the Minnesota River basin will aid in the development of management actions and the identification of priority management zones necessary to reduce sediment related impairments. Additionally, this work will provide baseline data and methodology for future work related to riparian vegetation, hydrology, and sediment within the Minnesota River basin.

With increasing flows on the mainstem Minnesota River in recent decades, point bars are spending more and more time submerged during the time when major riparian species germinate. This affects vegetation growth and composition on point bars. In comparing vegetation area relative to point bar area across recent years, in general vegetation area was found to increase during lower flow periods and decrease during high flow periods providing evidence for inhibited vegetation growth during high flows. Additionally, higher occurrence of saplings with adventitious growth habits were observed over those without adventitious habits indicating survival of these types of species, mainly willows, during high flow years of 2011 and 2013. In comparing historical flow data with tree core samples taken along the Minnesota River, trees were found to not have established in floodplains prior to high flows observed in the early 1950s and 1960s (or not survived the floods). Additionally, point bar vegetation was found to not be older than thirty or forty years providing evidence for succession from temporary point bar habitats to more permanent floodplain habitats. Lastly, sites in general that were characterized by more dense vegetation were found to have higher average rates of deposition based on a comparison of depth of sediment to root collar with plant age. This last finding is being investigated further via a series of experiments.

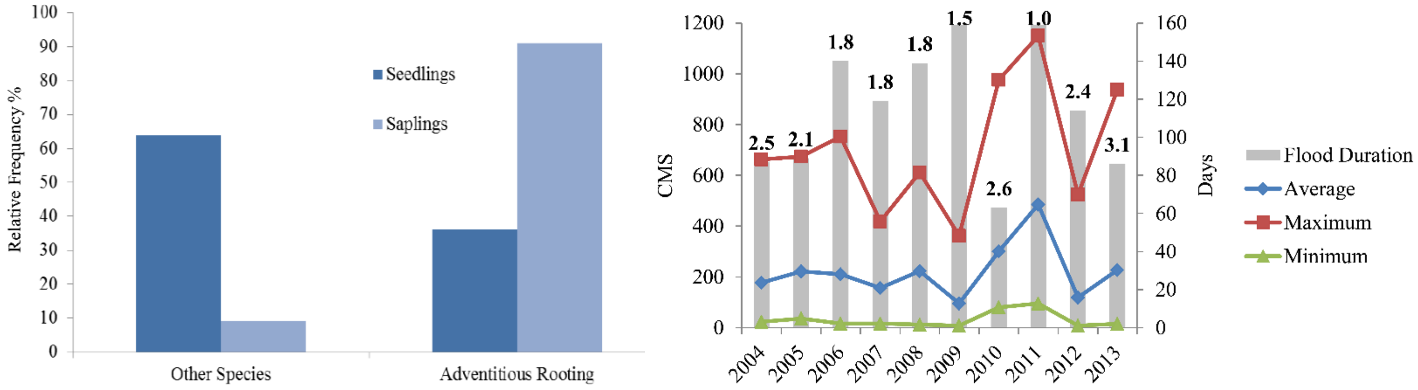


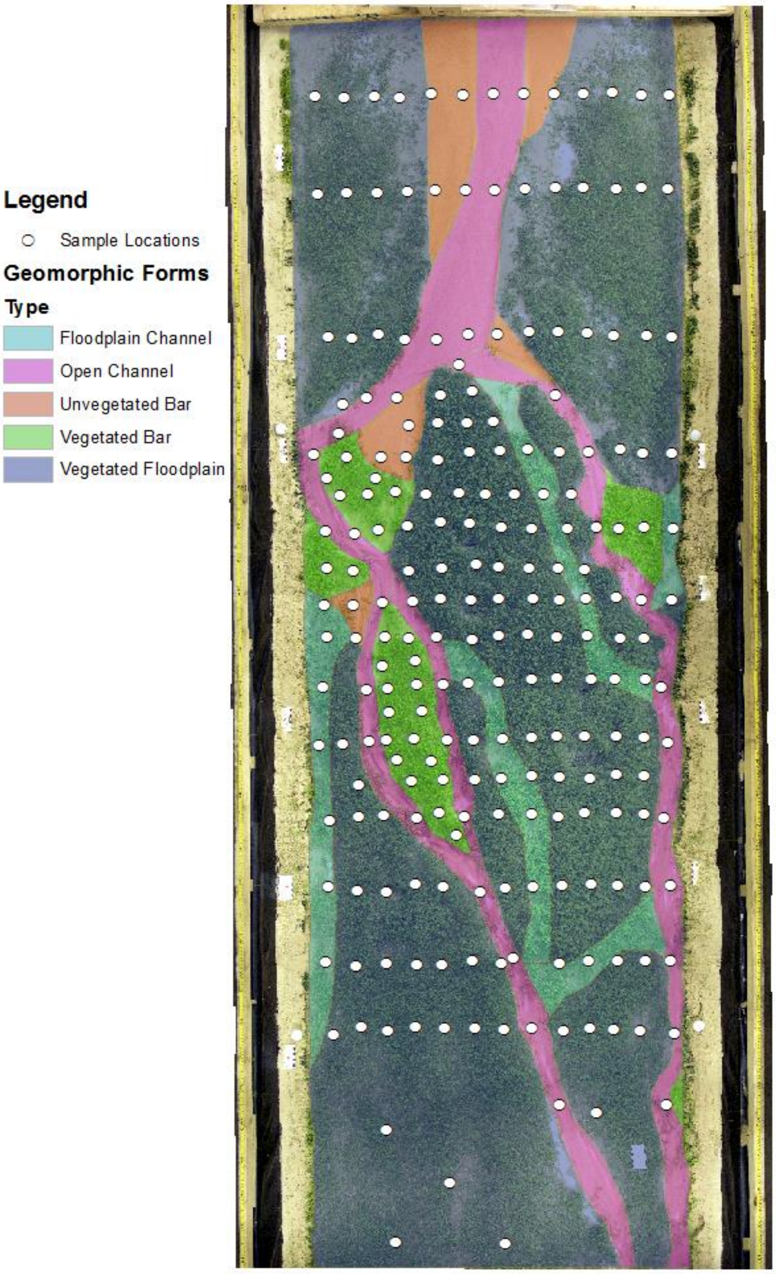
Figure 21. (left) Relative frequency of seedlings and saplings with normal vs. adventitious growth habits within lower Minnesota River basin transect surveys. N=82. (right) Recent flood characteristics in Minnesota River at Mankato, MN, including days of point bar inundation [from *Triplett*, 2015].

A series of flume experiments over the past decade have shown that riparian vegetation is a primary control on river morphology by adding surface cohesion and by trapping and storing suspended sediment. However, due to high spatial and temporal variability in the field, it is difficult to characterize the relationship between vegetation and flood deposition at a high resolution. A better understanding of how fine sediment is distributed through vegetated river corridors is crucial in determining the significance of floodplain storage in an overall sediment budget.

Building on the insights from previous experiments, we are experimentally investigating the role of vegetation density on the quantity and distribution of fine sediment in a self-formed channel network. Our approach is based on the understanding that riparian vegetation influences the spatial distribution of fine sediment deposition by its role in a) the organization of channel networks by the addition of floodplain cohesion, and b) the direct interruption of channel flow.

Our experiments are conducted in a 1.5 x 5 m flume at the University of Minnesota, Duluth. The flume is filled with 0.5 mm, graded to a slope of 1.5%. Water and sediment discharge rates are held constant. Once a braided channel network is established, we halve the water discharge and stop sediment feed to expose channel bars, which are seeded at a specified density. After a growth period of 7 days, discharge and sediment feed are returned and the run is continued. Flow is redistributed into one or two channel threads after two seeding events. We flush this channel network with lightweight plastic sediment in the final hour of the experiment, then remove core samples to characterize the quantity and spatial distribution of the resulting deposit. To date, we have completed one experiment with a high-density seeding. Two additional experiments, one with a low-density seeding and one without vegetation, will be completed by the end of the summer. Results of this study will provide crucial insight into vegetation-sediment feedbacks that contribute to fluvial landform building and channel evolution.

Figure 22. Overbank deposition of fine sediment within a patch of vegetation (alfalfa, Medicago sativa)



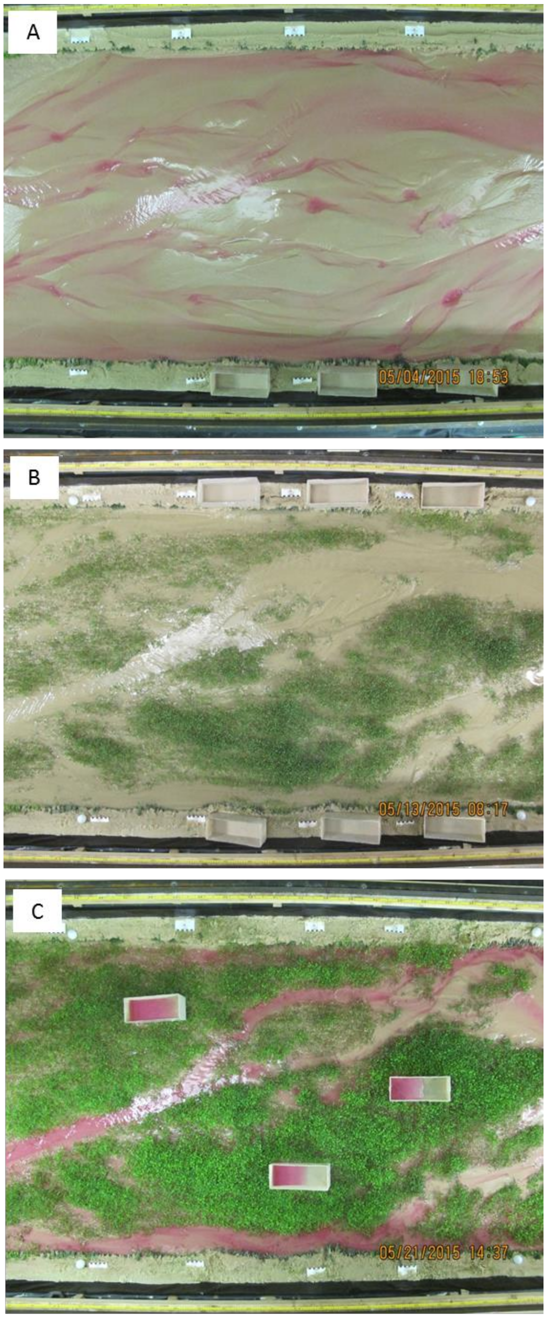


Figure 23. (left) Core samples extracted from the flume following the release of fine sediment.

Figure 24. (right) Reorganization of a braided channel network (A) following two seedings of alfalfa (B,C). Surface cohesion provided by the vegetation constrains channel flow into fewer threads.

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Gillian Roehrig's group:

Graduate Research Assistants: Senenge Andzenge, Engin Karahan,

Devarati Bhattacharya, and Justin McFadden

Overview

Building on the five aspects of collaboration and research earlier identified [*Roehrig et al*., 2014], year three of "The River Run: Professional Development with a Splash of Technology" documented marked progress in each area of (1) Continued teacher collaboration, (2) Curriculum development and classroom implementation, (3) Collaboration and collection of digital artifacts, (4) Socio-scientific issues and technology integration, and (5) Research presentations, articles, proposals.

1. Continued Teacher Collaboration

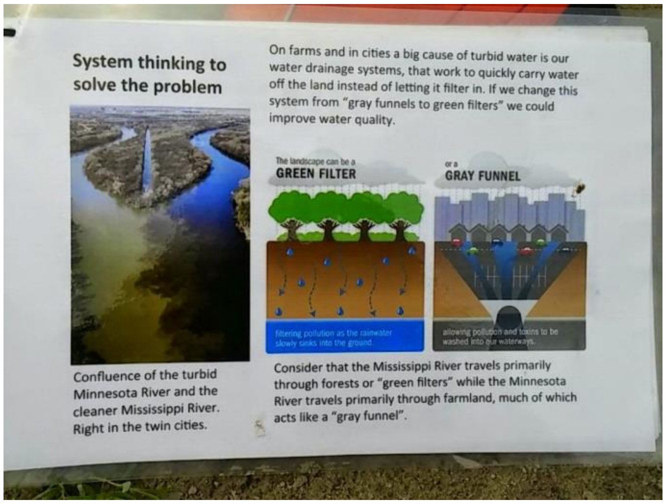
Table 1 in this section outlines and summarizes the collaborative efforts between educational researchers, high school science teachers, and high school students within the context of environmental science education during the 2014-2015 academic year.

Table 1. Educational support and outreach (2014-2015)

Date	Event	Description
Aug. 4th- Aug. 6th, 2104	**Active Learning Experience**	Immersion experience targeted specifically to secondary science teachers. Grounded within place-based and active learning frameworks, workshop topics included instructional strategies and activities for teaching and learning about: formation and ecology of rivers and watersheds, causes and contributors to turbidity, historical, cultural, agricultural development of river civilizations
Aug. 6th- Aug. 7th, 2014	**Curriculum Development**	Development of Content Knowledge specific curriculum geared towards teaching and learning about environmental science within the context of the Minnesota River Basin (MRB) watershed.
Aug. 7th, 2014	**Teacher Enrichment**	Extensive tour the St. Anthony Falls Laboratory (SAFL) research and educational facility. Session emphasis on the availability of SAFL research and facilities to support teaching environmental science relevant to the contexts of MRB secondary science learners

Oct. 2014-June 2015	**On-going coaching and support**	Periodic check-in via face-to-face, email, and telephone
December 2014	**Fall Semester Meeting**	Co-constructed a platform for Spring 2015 Pilot of teaching and learning environmental science grounded within a service learning framework
May 2015	**Spring Semester Meeting**	Reflection on practice: successes, learning opportunities, direction forward using service learning as a framework for teaching and learning environmental science within the context of the Minnesota River Basin.

Active Learning Experience (Aug. 4-6, 2014): This fully immersive active learning intervention was experienced in partnership with Wilderness Inquiry, Ranger Dave Wiggins (National Parks Service), and Secondary School teachers from St. Paul Public Schools. Through formal and informal learning activities, various contexts for teaching and learning environmental science content were explored and shared. Situating discussions of watershed ecology in different historical and cultural contexts invited teachers to practice and expanded on their pedagogical knowledge of environmental science content. Further, the experience offered the teachers inventive ways of connecting foundational science content, emerging learning technologies to address real-world problems within authentic learning environments.



System thinking to solve the problem

On farms and in cities a big cause of turbid water is our water drainage systems, that work to quickly carry water off the land instead of letting it filter in. If we change this system from "gray funnels to green filters" we could improve water quality.

Confluence of the turbid Minnesota River and the cleaner Mississippi River. Right in the twin cities.

Consider that the Mississippi River travels primarily through forests or "green filters" while the Minnesota River travels primarily through farmland, much of which acts like a "gray funnel".

Curriculum Development (Aug. 6-7, 2014): This collaborative experience between the research team and the teachers was a session to share and apply ideas to developing classroom curriculum, both within specific disciplines and interdisciplinary. Teachers drew from their existing and new pedagogical and content knowledge to address teaching objectives and student learning goals in areas of environmental science.

Fall Semester Meeting (December 2014): Using a shared construct of service learning, researchers and teachers co-constructed a platform for teaching and learning environmental science which could focus direct-instruction practices around student-centered constructivist learning experiences. Products from this session would pilot as appropriate in the teacher classrooms during Spring 2015 semester.

Spring Semester Meeting (May 2015): The teachers and research team met face-to-face to share success, learning opportunities, and evaluate the experiences of using service learning as a framework for teaching environmental science within the context of the Minnesota River Basin. The group set an agenda of topics to develop and work into curriculum which could add depth to teaching and learning environmental science.

2. Curriculum Development and Classroom Implementation

A primary focus in curriculum development this year included efforts to address specific types of lessons within teaching and learning environmental science which could be highlighted from its interdisciplinary nature to emphasize particular disciplines as warranted and appropriate. The curriculum incorporates classroom lecture and discussion suggestions, case study libraries, project design activities, short supporting lessons, and larger-scope interactive group research projects.

During spring semester 2015 secondary science student-groups from schools across the Minnesota River Basin engaged in various project-based and service learning experiences, exploring themes in environmental science including watershed ecology, plant and animal biology, river formation, land and watershed management, and human impacts on nature.

Examples of developed curricula can be found on the project site at this link (http://stem-projects.umn.edu/riverrun/test-page/)

Project-Based environmental ethics lesson: Teachers and students wrote and received a grant to build a rain garden at the high school. In building the rain garden, student lessons and discussions included: Non Point source pollutants and their impact on Water quality, Sedimentation and its impact on water quality, Tile design and conceptual understanding, Data analysis between tiled and untilled field (water flow).

3. Collaboration and collection of digital artifacts

Technology use focused on supporting pedagogy and developing technological-pedagogical competence with the teachers. Teachers leveraged their expanding knowledge of resources and context for teaching environmental science to access new pedagogies for embracing mobile and other emerging technologies. Student groups from three of four teachers involved in this experience produced end of semester multi-media productions showcasing an important socio-scientific issues relative to their community within the Minnesota River Basin. Student-groups in these cases identified a real world problem relative to their community in the Minnesota River Basin, researched and investigated the issue, consulted with local experts, and shared their findings with their communities.

For ease of access and usability, teachers had individual students and student groups document data collection and other research activities using online blogs.

<u>**Environmental ethics land management lesson:**</u> (stills from a video project)

4. Socioscientific and Technology Integration Educational Research

This area has represented a significant area of focus in our research on teaching and learning environmental science in the context of the Minnesota River Basin. Addressing socioscientific issues has been one of the main focuses in science education since the Science, Technology, and Society (STS) movement in the 1970s. Despite generally positive attitudes for using controversial socioscientific issues in their science classrooms, only a small percentage of science teachers actually incorporate SSI content into their science curricula on a regular basis. Developing learner's 21st century skills is fueling many efforts in teacher education. For in-service teachers, professional development opportunities can be a catalyst for reinforcing pedagogical skills with technological knowledge and communicating content in ways that are meaningful and engaging to students. Current science education reforms in the U.S., driven by the Next Generation Science Standards, places heightened emphasis on preparing students for futures in STEM fields. This, therefore, makes it imperative that science teachers integrate technology into their science instruction.

5. Research Presentations, Articles, Proposals

The educational outreach team has, thus far, presented or had the following papers accepted pending presentation at international and regional conferences during 2014-2015:

Karahan, E (2015). Secondary School Teachers' Expereinces of Designing and Teaching Sociocientific Issues-Based Classes and their Students' Understanding of Science and Socioscientific Reasoning. *Doctoral Dissertation, University of Minnesota*.

Karahan, E., Andzenge, S.T., Roehrig, G. (August 2015). Engaging students in community-based issues through authentic problem-based learning experiences. *Paper presentation (accepted) at the annual meeting of the European Science Education Research Association (ESERA), Helsinki, Finland*.

Andzenge, S.T., Karahan, E., Roehrig, G. (July, 2015). Digital Natives, Immigrants, and TPACK: an exploration of secondary science teachers and technology. *Paper presentation (accepted) at the annual MNeLearning Summit, Minenapolis, MN*.

Andzenge, S.T., Karahan, E., Bhattacharya, D., Roehrig, G. (April 2015). Eliciting students' understanding of river geography and socioscientific issues through a critical response protocol. *Paper accepted for presentation at the annual meeting of the National Association of Research in Science Teaching (NARST), Chicago, IL.*

Andzenge, S.T., Karahan, E., Bhattacharya, D., Roehrig, G. (November 2014). Technology integration and water sustainability in STEM education: A professional development experience. *Paper presented at the annual meeting of the Association for Educational Communications and Technology (AECT), Jacksonville, FL.*

McFadden, J. (November 2014).The River Run: Professional development with a splash of technology. *Mississippi River Education Symposium, East Alton, IL.*

Karahan, E., Andzenge, S.T., Bhattacharya, D., Roehrig, G. (November 2014). A technology rich professional development program and its influence on participant teachers' practices. *Paper presented at the annual meeting of the Association for Educational Communications and Technology (AECT), Jacksonville, FL.*

Patrick Belmont

Department of Watershed Sciences

Utah State University

Year 3 Research Results from REACH

NSF Water, Sustainability and Climate project (CBET 1209445)

REACH
Resilience under
Accelerated
Change

This document contains the research summary for the NSF WSC REACH project for year 3 (2014-2015) for PI Patrick Belmont at Utah State University.

Patrick Belmont's students contributing to this project include: Karthik Kumarasamy (post-doctoral researcher), Sara Kelly (PhD candidate), Keelin Schaffrath (PhD candidate), Mitchell Donovan (PhD student), Angus Vaughan (MS student), Shayler Levine (undergrad), Adam Fisher (undergrad), Patrick Adams (undergrad).

Research themes and accomplishments during 2014-2015

The Utah State University-based REACH research group has taken the lead on several initiatives during year 3, including 1) analysis of high resolution topography data, 2) analysis of discharge-suspended sediment relationships for rivers throughout the state of Minnesota, 3) mapping of river channel bathymetry, and 4) watershed hydrology and sediment modeling. Application of the tools and techniques has been concentrated primarily on the Minnesota River Basin, but all are generalizable and portable.

1. Analysis of high resolution topography data

My research group has initiated several studies that expand our capabilities to measure landscape change over relatively short timescales. We have been working at small spatial scales (individual bluffs in the Le Sueur River Basin) to measure erosion with high frequency (daily) using an automated system we designed for structure-from-motion photogrammetry. We have recently completed a study at very large spatial scales (1950 km^2) to measure 'meaningful' change at the landscape scale using two repeat aerial lidar datasets from 2005 and 2012, covering Blue Earth County in south-central Minnesota (including the most active parts of the Le Sueur River Basin). In addition, myself and two of my PhD students were co-authors on a comprehensive review of "Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes", currently in press with Earth Science Reviews.

Passalacqua, P., Belmont, P., Staley, D.M., Simley, J.D., Arrowsmith, J.R., Bode, C.E., Crosby, C., DeLong, S.B., Glenn, N.F., Kelly, S.A., Lague, D., Sangireddy, H., Schaffrath, K.R., Tarboton, D.G., Wasklewicz, T., Wheaton, J.M. (in press) Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. Earth Science Reviews.

1a. Geomorphic change detection over vast areas with spatially variable uncertainty

Repeat surveys of high-resolution topography data enable analysis of geomorphic change and such analyses are becoming increasingly common. However, techniques for developing robust estimates of spatially variable uncertainty have been slow to develop and are underutilized. Further, issues are often encountered in comparing recent to older datasets, due to differences in data quality. Airborne lidar data were collected in 2005 and 2012 in Blue Earth County, Minnesota (1,980 km^2, see Figure 1) and the occurrence of an extreme flood in 2010 produced geomorphic change clearly observed in the field, providing an opportunity to estimate landscape-scale geomorphic change. Initial assessments of the lidar-derived digital elevation models (DEMs) indicated both a vertical bias due to different geoid models and a localized offset strips in the DEM of difference, due to poor co-registration of the flightlines. We tested several approaches to correct for the poor flight line co-registration, including a Fourier transform filter and a spatially variable correction surface that was generated using local, empirical estimates of the offset, the latter of which most effectively corrected for the bias (Figure 2). We then compare different threshold models to quantify uncertainty. Poor quantification of uncertainty can artificially inflate estimates of change and underreport areas of real change. We show the application of a uniform threshold, often called a minimum level of detection, overestimates change in areas where change would not be expected, such as stable hillslopes, and underestimates change in areas where it is expected and has been observed, such as channel banks. Therefore, we developed a spatially-propagated error model applied to the DEM of difference that quantifies uncertainty based on slope, point density, and vegetation in each square meter pixel in the area analyzed (Figure 3). To support the spatially variable error model, we developed a new metric (cloud point density ratio) to quantify uncertainty due to vegetation density by capitalizing on the complete point cloud to describe the density of above-ground features that may prevent the laser from hitting bare earth. It is calculated by taking the ratio of the above-ground point density to the total point cloud point density. Beyond the methodological advances, our results indicate net erosion of 2,625,100 m^3 in the county between 2005 and 2012. Of this, 39% was generated from bluffs, 1% from ravines, and the remainder came from banks and floodplain areas.

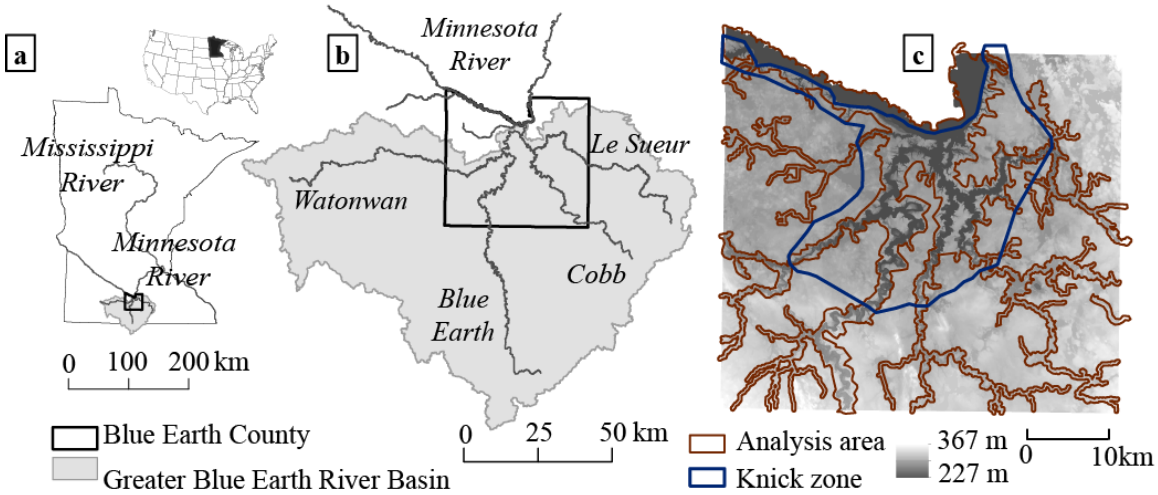


Figure 1. Map of the state of Minnesota showing the Minnesota and Mississippi Rivers and the location of Blue Earth County and the Greater Blue Earth River Basin.

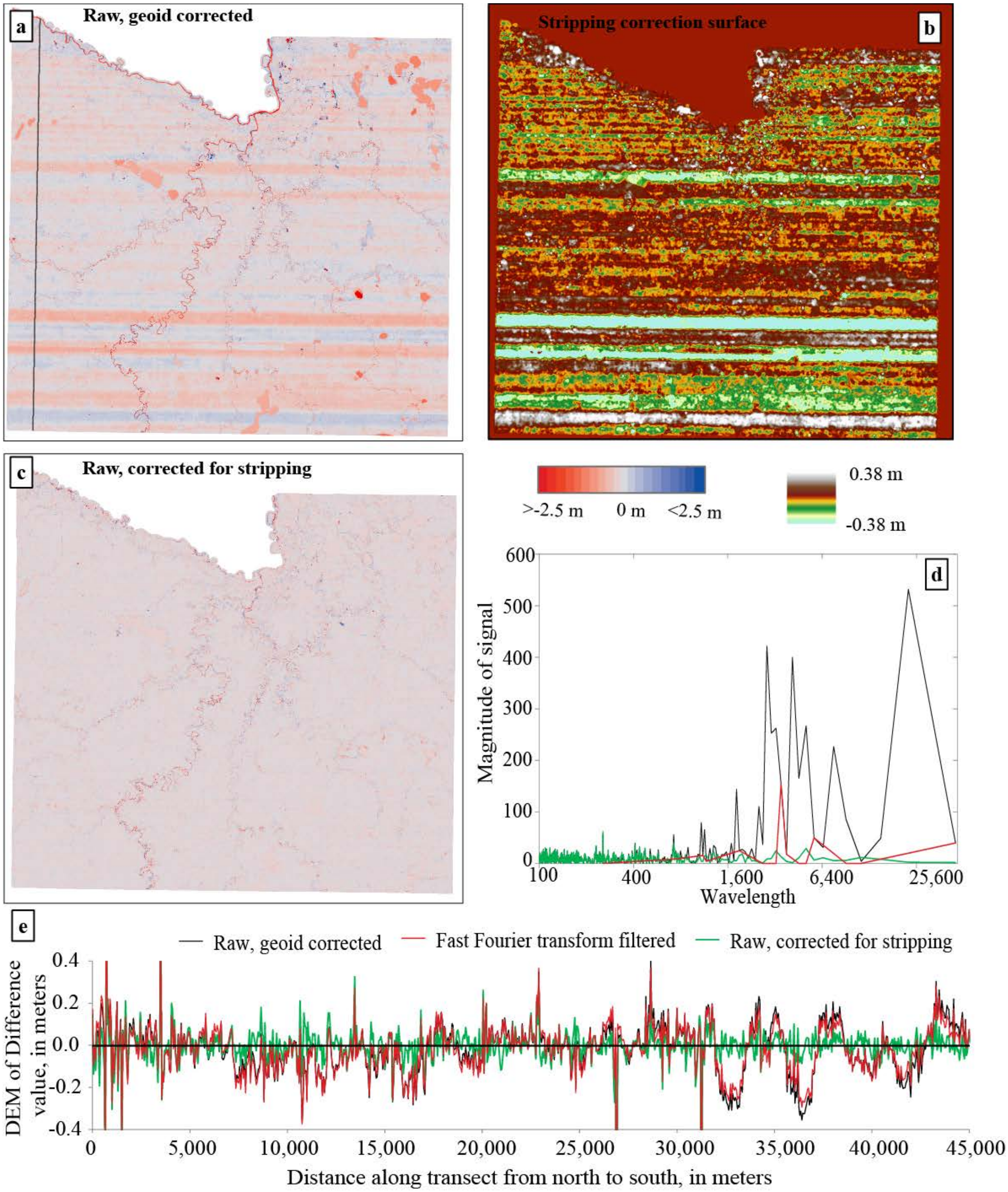


Figure 2. Maps and plots showing the initial characteristics associated with stripping and the correction applied. a) geoid-corrected DEM of Difference showing distinct strips in the east-west direction and the north to south transect, for which we extracted the elevation profile. b) Surface generated to correct the stripping problem. c) DEM of Difference corrected for stripping. Note the east-west strips are no longer evident and the surface is a mix of red (erosion) and blue (deposition). Two plots (d-e) in the figure correspond with data collected at

points on a 50-meter interval on the line shown in the top left panel. d) Power spectra plot where the black line refers to the data from the geoid-corrected DEM of Difference, the red line is the output after a filter based on a fast Fourier transform, and the green line is the output after the application of the stripping correction. e) Elevation profile shows the DEM of difference values for the geoid-corrected (black), fast Fourier transform filtered (red), and final stripping correction (green).

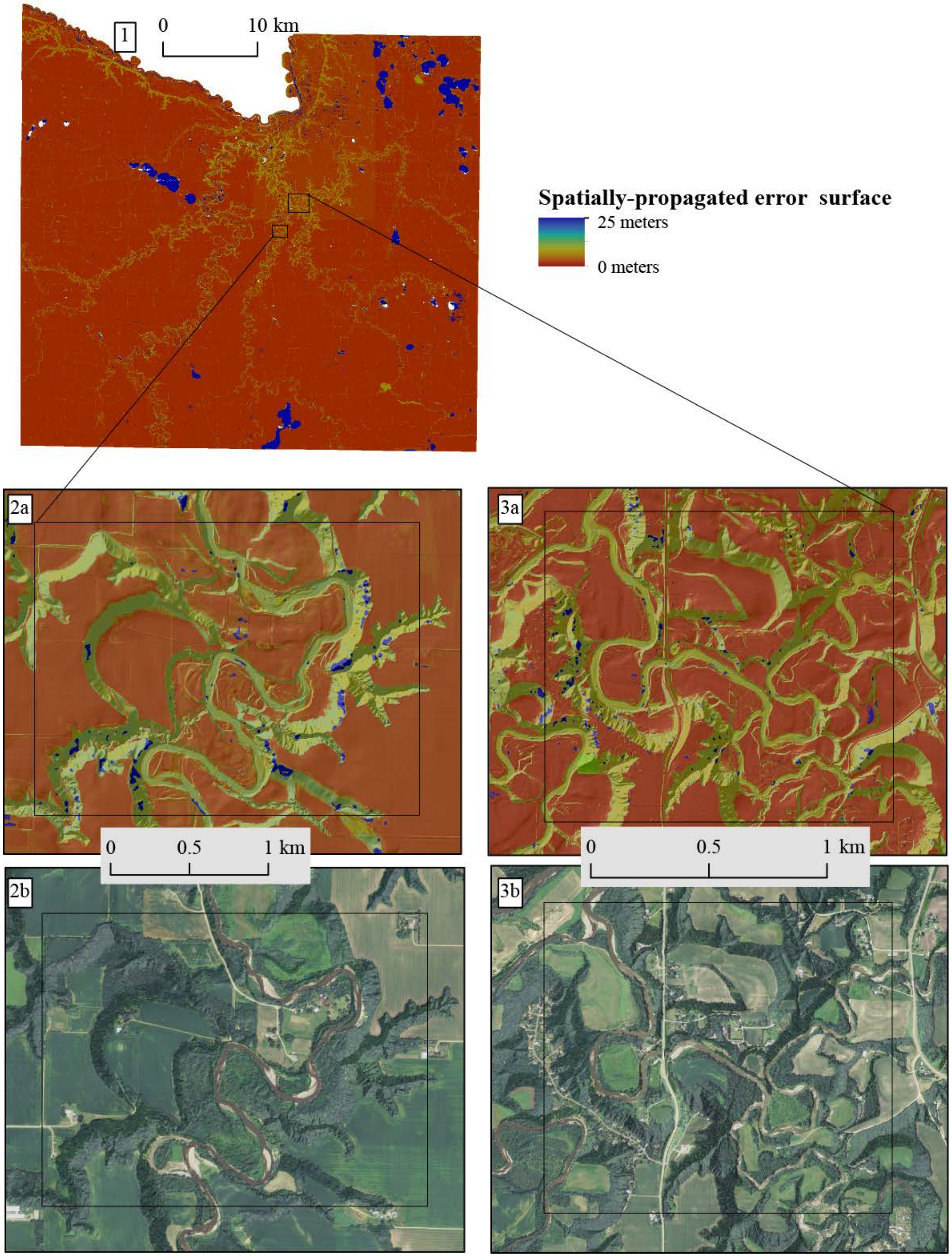


Figure 3. Final surface of spatially-propagated error model for Blue Earth County (panel 1). Equation 1 in the text describes how this surface was calculated. For additional detail, two additional panels are shown at finer scale and underlain by the 2012 hillshade model in areas also used to test the thresholding methods. Panels 2a and 2b show the a) spatially-propagated error model b) and orthophoto for the area used to test different values of minimum level of detection and Panels 3a and 3b are of the area used to test different fuzzy inference systems.

1b. Geomorphic change detection over small spatial scales with high temporal frequency

Excess sediment is problematic in many river systems. The Le Sueur River basin, south central Minnesota, contributes a disproportionate amount of fine sediment to the Minnesota River, which is listed as impaired for sediment under the Clean Water Act, section 303d. High sediment loads can be attributed to the geologic history of the basin over the Holocene as well as agricultural expansion and intensification over the last century and a half. A modern fine sediment budget completed for the Le Sueur River suggests that riverine buffs contribute the greatest proportion of fine sediment to the total sediment load (Day et al. 2013; Belmont et al. 2011), and are likely to be the source all of the coarse bedload material.

Previous research studies of the Le Sueur River have used terrestrial laser scanning(TLS) on an annual to biannual basis to compute volumes of bluff erosion and deposition using geomorphic change detection (Day et al. 2013). This research demonstrated a positive relation between erosion volumes and peak flows between scans. One hypothesis is that high shear stresses at the toe of the bluff lead to toe erosion, over steepening of the bluff, and eventually failure. Another hypothesis is that positive pore water pressures reduce the shear strength of bluff till and lead to mass failures. These hypotheses are not mutually exclusive. We plan to test the importance of both of these hypotheses using field observations and physically-based modeling. We will build and validate a hydraulic and bluff erosion model at two actively eroding bluffs on the Le Sueur River (Figure 4). We have collected bathymetry, velocity, discharge, water surface elevation and grain size distribution data at each of the bluff sites. We established a Structure from Motion (SfM) photogrammetry platform in April 2013 to take daily photographs of the bluffs for calculations of geomorphic change. Photos from the first 16 months of observation have indicated a total of 18 significant erosion events (Figure 5). Ongoing work is quantifying the total amount of sediment eroded during each of these events, which will be used to develop a process-based model of bluff erosion. In May 2015 we installed 20 additional trail cameras that will take daily photographs of bluffs distributed throughout the Le Sueur, Blue Earth and Watonwan rivers.

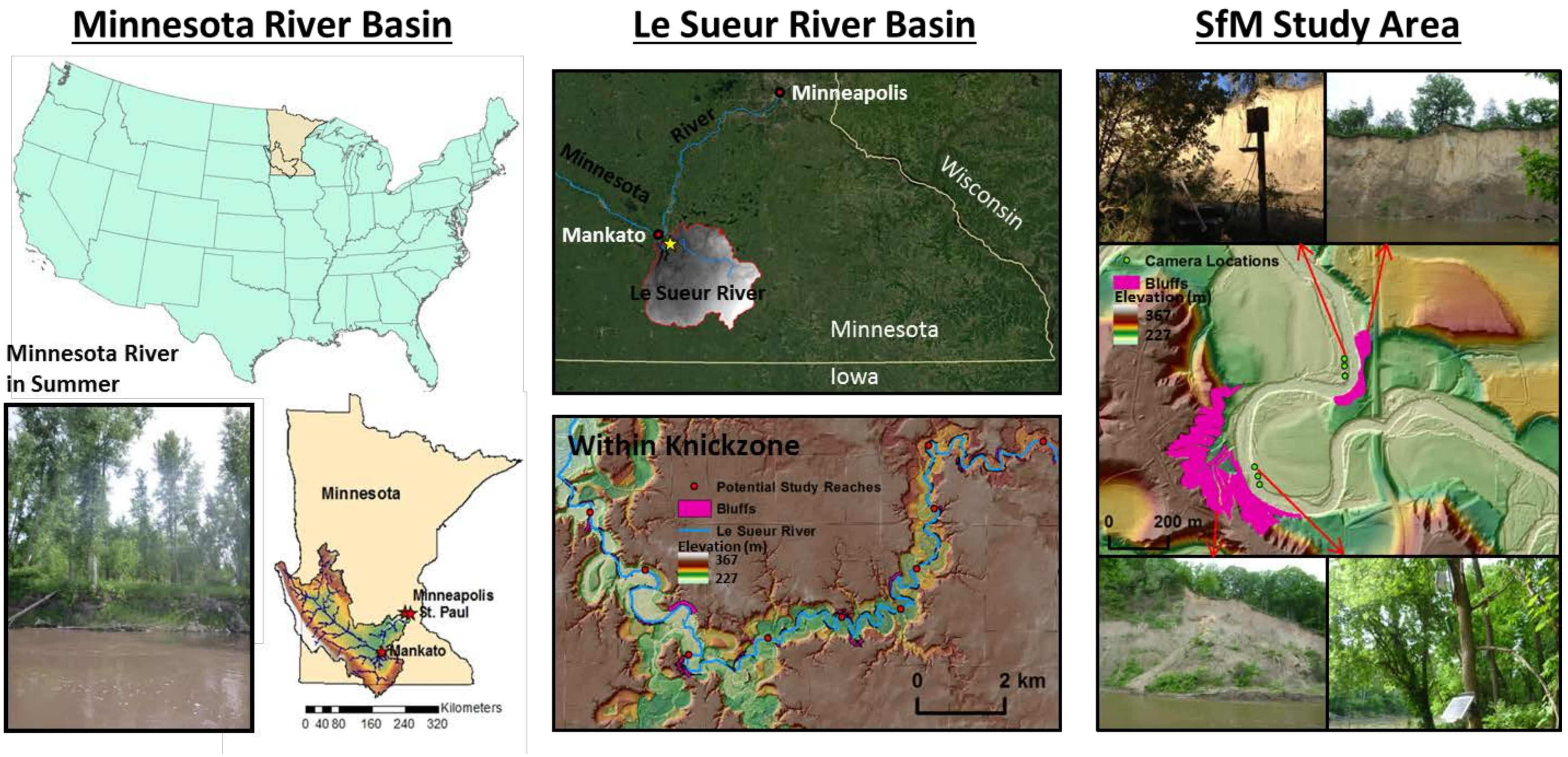


Figure 4. Left: Overview map of the Minnesota River basin with photo of the Minnesota River in summer. Center: Location of the Le Sueur River basin (watershed boundary in red) and close up DEM within the knickzone highlighting bluff locations in pink. Right: Locations of the Structure from Motion remote sensing platform with photos of the overly consolidated bluff above and the normally consolidated slump below.

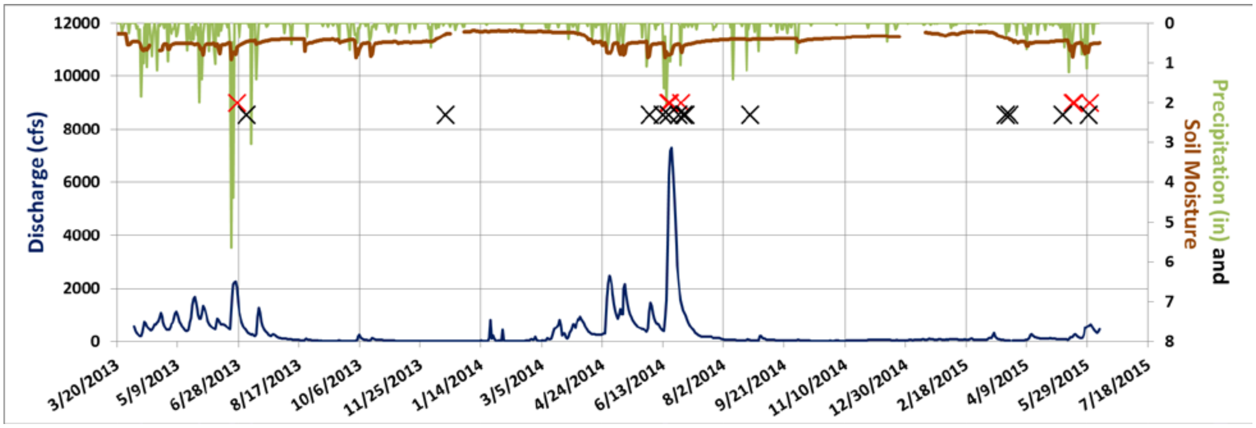


Figure 5. Results from 15 months of Structure from Motion monitoring of two bluffs in the Le Sueur watershed, southern Minnesota. Instances of bluff erosion (indicated by black Xs for the upstream, normally-consolidated bluff and red Xs for the downstream, over-consolidated bluff) are indicated with respect to discharge (blue line), precipitation (green bars) and soil moisture (orange line). Ongoing work is modeling the various erosional processes that occur under different conditions.

2. Analysis of discharge-suspended sediment relationships for rivers throughout the state of Minnesota

Minnesota regulates suspended sediment loads by grouping watersheds into four nutrient regions: rivers in the northern, central, and southern regions and the Red River of the North mainstem each have separate suspended sediment standards (Figure 6). Total Suspended Solids (TSS) concentrations are required to not exceed 15, 30, 65 or 100 mg/L, respectively, more than 10 percent of the time over a multiyear window. The regional criteria are based on two lines of evidence: 1) statistical analyses of paired biological and water quality (i.e. TSS) data to determine ecologically damaging threshold TSS concentrations and 2) analysis of TSS data from “least impacted” and reference streams (Minnesota Pollution Control Agency, 2011). The different standards are, to some extent, a recognition of the different suspended sediment regimes in different parts of the state, produced by diverse geologic, geomorphic, climatic and land use settings and histories. However, the boundaries are based on the regions used to regulate nutrients, for which transport and delivery processes do not entirely overlap with those for sediment. A likely result of that mismatch is that the TSS standards for some rivers may not be consistent with the geomorphic settings and processes that control sediment delivery to the river network. This research is aiming to achieve a more detailed understanding of the factors controlling sediment regimes across the state. There is good reason to believe sediment supply and transport regimes vary systematically across the state, based on unique geologic, climatic, hydrologic, geomorphic and land use settings and histories.

Suspended sediment is often a non-capacity load; transport rates are dependent not only on the transport capacity of the river, but also on the availability of fine sediment. Therefore, stream power-driven transport models such as those used for bed load prediction are not suitable, and empirical relations are used instead. Sediment rating curves describe the average relation between river discharge (Q) and SSC at the location where the data were measured; the curves are typically derived from statistical regression on the Q and SSC data. The curves most commonly take the form of a power function:

$$SSC = aQ^b \quad (1)$$

where *a* and *b* are the sediment rating coefficient and exponent (Asselman, 2000; Fan et al., 2012; Hu et al., 2011; Mimikou, 1982; Sadeghi et al., 2008; Syvitski et al., 2000; Warrick, 2014; Yang et al., 2007). Power function curves imply continually increasing SSC with increasing Q; they incorporate the influence of amplified stream power at greater discharge as well as the degree to which new sediment sources are accessed during conditions that cause high discharge (Figure 7). Figure 8 maps the magnitude of the exponent (b) in Equation 1 for all gages that have 10 or more years of data since the year 2000. The spatial patterns indicate steep power function relationships in the lower reaches of Minnesota River tributaries (in the knick zone reaches responding to base level fall, as documented by Belmont, 2011 as well as in southeastern Minnesota, where steep bedrock channels debouch into wide, low gradient alluvial valleys. With the conceptual understanding that channel dynamics (meander migration, fluvial undercutting of bluffs, channel widening, etc.) are likely controlling these Q/TSS relations, we are working to extract near-channel morphometrics to explain these spatial patterns.

Understanding the controls on Q/TSS relationships remains an intriguing topic from a basic science perspective, especially with the availability of high resolution topography data and increasing computational power that can take advantage of the immense amount of information contained therein. Understanding differences among Q/TSS relationships also has important implications for land and water management, insofar as they are indicators of sensitivity and vulnerability of systems to erosion. We seek to understand spatial and temporal patterns in those relationships by asking the following questions:

1.) Which landscape or channel characteristics most influence the shape of Q/TSS relationships? Why are some river systems more sensitive to increases in discharge than others? Do Q/TSS relationships vary seasonally?

2.) How can a better predictive understanding of Q/TSS relations be used to improve existing water quality regulations, water and land management, and restoration practices?

3.) Have TSS concentrations changed over time? How do non-stationary hydrologic conditions affect Q/TSS relationships? To what extent can Q/TSS rating relations be used to forecast TSS concentrations under altered hydrologic regimes?

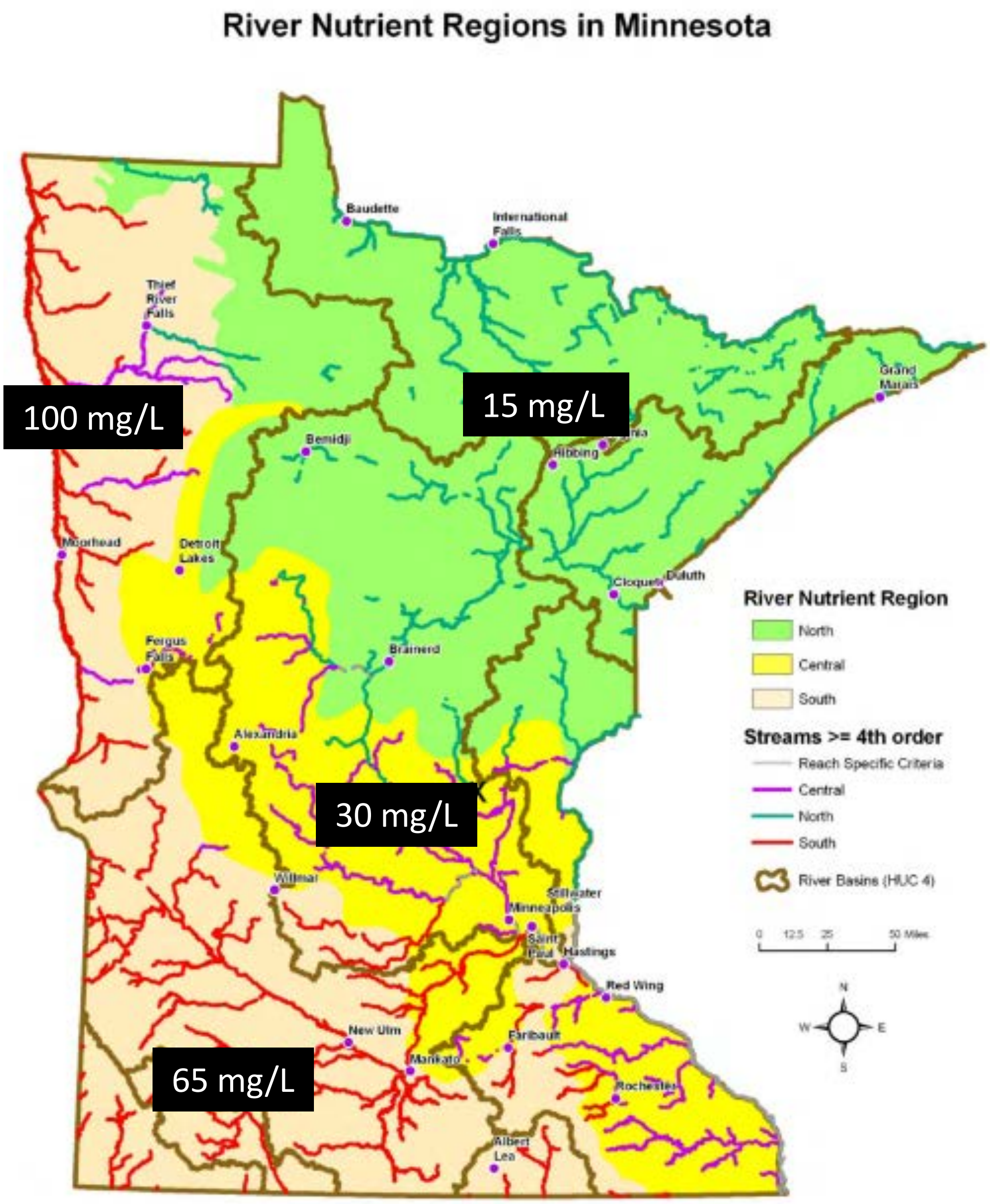


Figure 6. River Nutrient Regions for Minnesota, with TSS concentration thresholds shown. From Minnesota Pollution Control Agency (2011).

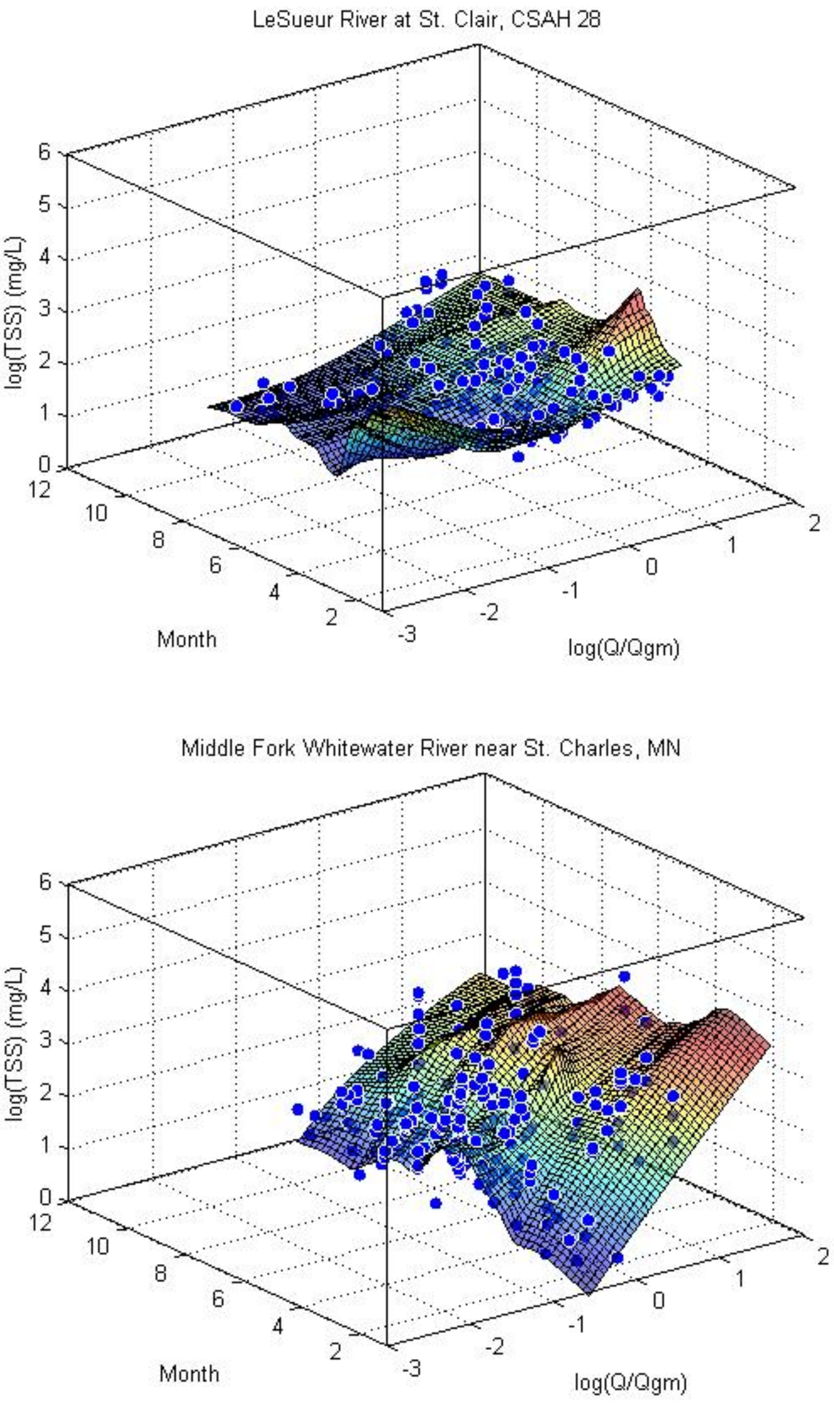


Figure 7. Examples of Q/TSS relationships with fitted LOWESS surfaces, showing seasonal variation in the Q/TSS relationship. Data are from (top) the Le Sueur River at St. Clair, MN and (bottom) The Middle Fork of the Whitewater River near St. Charles, MN.

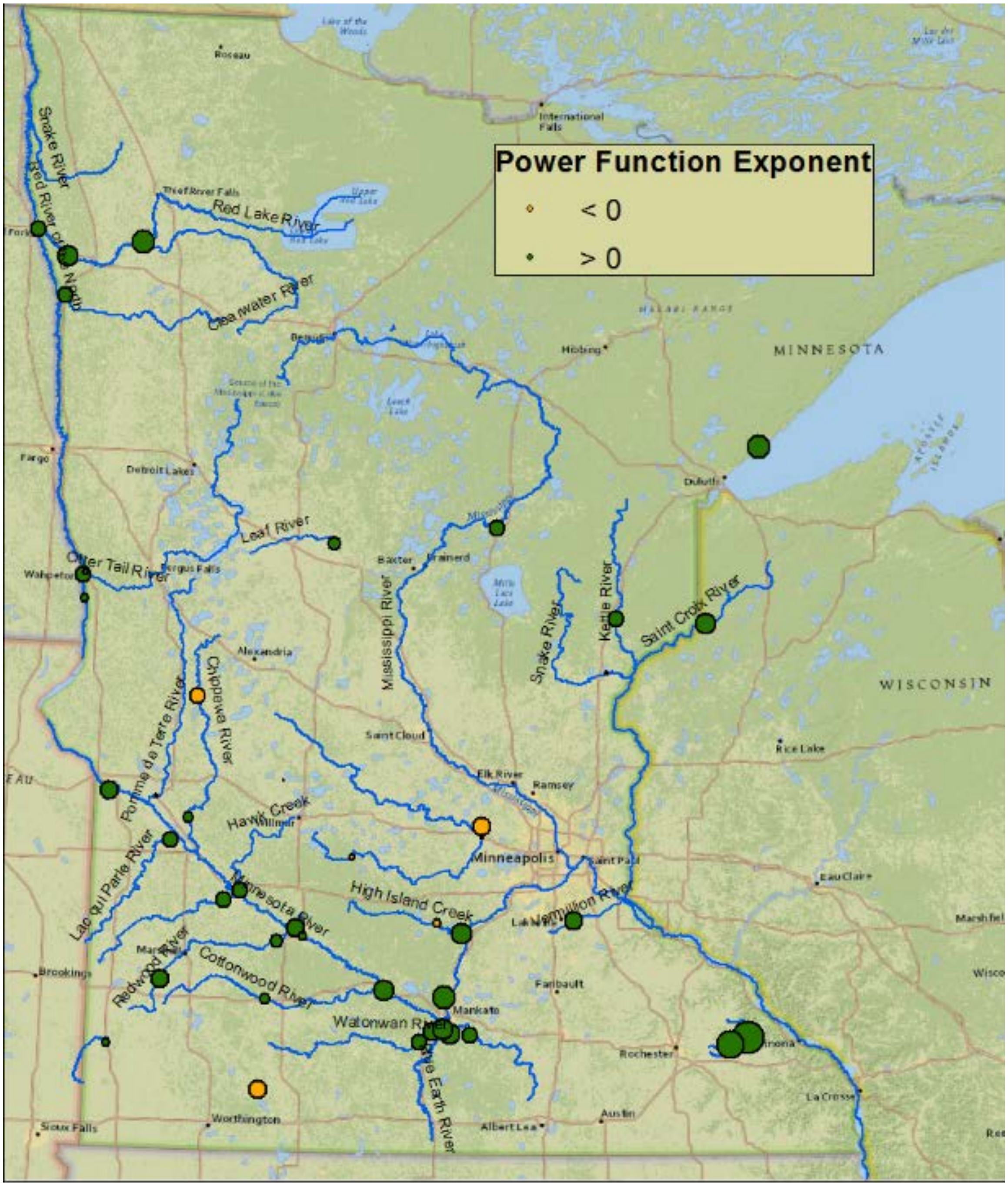


Figure 8. Power function exponent values for study gages. Dots representing gages are sized according to the value of the exponent. Negative exponents are shown in orange, positive exponents in green. Note the large exponents in MRB tributary gages near the confluence with the Minnesota River (i.e. within the knickzone) as well as in the southeastern part of the state and in some of the Red River of the North tributaries. Small or negative values occur in MRB tributary gages above the knickzone and in Upper Mississippi tributaries.

3. Mapping channel bathymetry

High resolution topography data from aerial lidar is dramatically enhancing our abilities to identify critical features and measure geomorphic change over vast areas. However, most lidar datasets do not contain topography data within the channel itself because the wavelengths utilized are fully attenuated even in shallow water. This is especially concerning because river channel networks tend to be the most dynamic 1% of the landscape. Because REACH is strongly focused on understanding in-channel dynamics, obtaining accurate maps of channel bathymetry over large areas is critical.

Beginning in summer 2013 and continuing in summer 2015 we are mapping extensive areas of the Minnesota River and Le Sueur River channel beds using an Acoustic Doppler Current Profiler coupled with a real-time-kinematic GPS system. We have developed a system that allows our rtkGPS to tie into the Minnesota Department of Transportation Continuously Operating Reference Station Network, using a CDMA-enabled cell phone. This allows us to get real-time corrections for GPS locations with precision of 2-3 cm. All of this instrumentation is loaded on a 17' cataraft with an outboard motor and data is assimilated on a laptop or tablet computer (Figure 9, top panel). As of summer 2015, we have mapped a total of 110 km of the mainstem Minnesota River. The resulting datasets will be used for modeling of hydrology, morphodynamics, light penetration, mussel habitat, and nutrient assimilation.

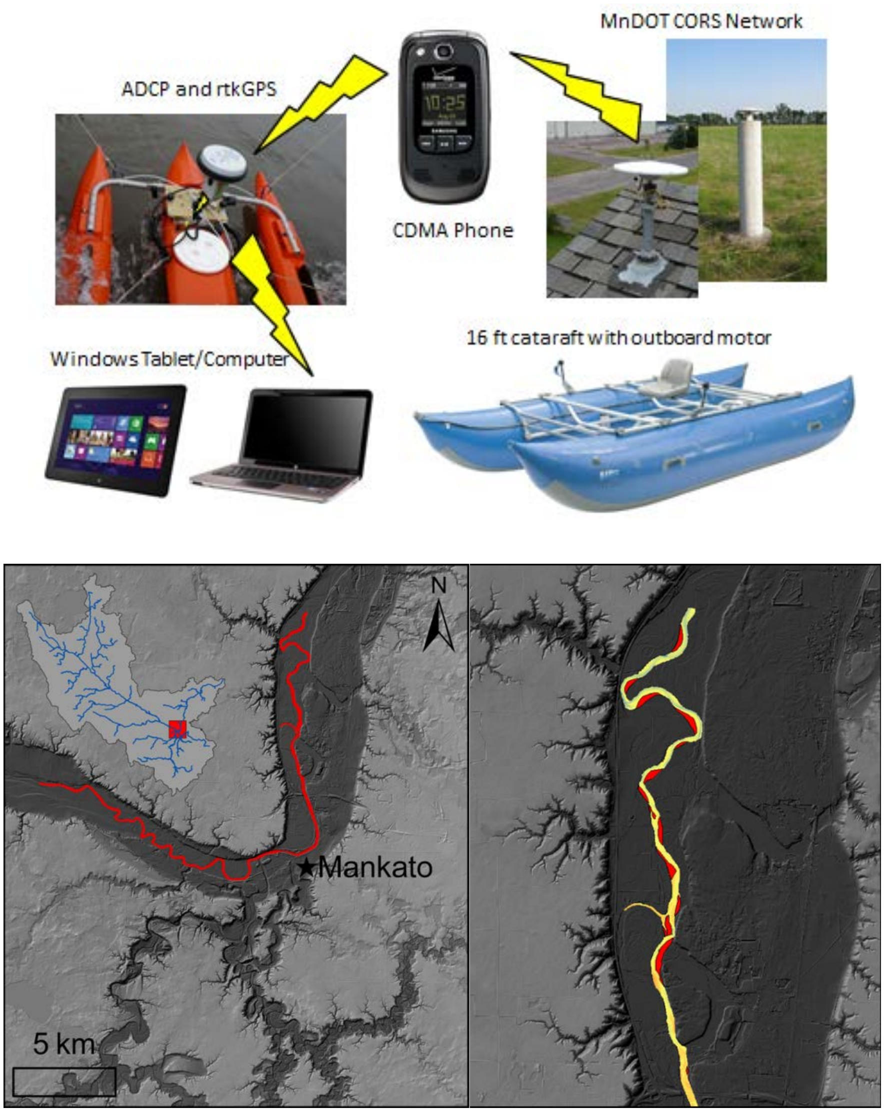


Figure 9. Top Panel: illustrates our system for rapid channel bathymetry mapping. Bottom Panel: show the 33 km reach of the mainstem Minnesota River that we were able to map in six days during summer 2013.

My research group will be utilizing this bathymetric dataset along with morphodynamic modeling to explain how local sediment supply, bank cohesion, and bar morphology interact with bed topography and hydraulics to control meander migration rates and morphodynamics in the Le Sueur and Minnesota Rivers, south central Minnesota. In a complementary pilot study, we will be exploring the same phenomena in the Fall River, Rocky Mountain National Park, Colorado. These meandering rivers provide unique opportunities to identify and model how local sediment supply, bank cohesion, and bar morphology interact with bed topography and hydraulics to control meander migration rates and morphodynamic evolution in strikingly different alluvial valley settings, with differences in slope, valley confinement, and lithology. Specifically, we hypothesize that reaches with local, coarse sediment supplies will exhibit faster rates of morphodynamic change and meander migration than reaches without such supply, all else constant.

There are important feedbacks between coarse sediment, channel topography, and meander migration. Bedload sediment transport is necessary for the creation of channel bedforms. Large bedforms or macroforms, such as bars, topographically steer flow toward the opposite bank, which promotes meander migration (Church and Rice 2009; Ikeda et al. 1981; Dietrich and Smith 1983). Conversely, an imposed meandering planform encourages bar deposition and meander migration (Harrison et al. 2011). Accordingly, we hypothesize that meandering rivers that have access to a local bedload supply at the channel margins will construct bedforms, migrate faster, and thus recruit more material from the channel margins. We expect to capture this positive feedback in natural river reaches and morphodynamic models.

4. Watershed hydrology and sediment modeling

REACH is developing innovative and robust ways to model rainfall-runoff and implications for erosion, transport and deposition of sediment as well as transport and assimilation of nutrients. We have chosen to develop a set of nested Soil and Water Assessment Tool (SWAT) models for the entire Minnesota River Basin, Greater Blue Earth River Basin, and Le Sueur River Basin. SWAT is commonly applied for watershed-scale planning and management and has an enormous user base of researchers, federal, state and local agency staff, and industry professionals. The model is quite useful for making some predictions (e.g., rainfall-runoff simulation), but has critical problems in other areas (e.g., it does not simulate channel dynamics in any process-oriented manner). Thus, we plan to use the robust components of the model to provide inputs to more sophisticated models and plan to provide new solutions to improve components that are currently inadequate. In addition, this model serves as an efficient interface between our economic and biophysical models.

Changes in hydrology resulting from tile drainage and land use change have been implicated as the primary drivers of failing water quality objectives relating to higher turbidity in the Le Sueur River basin (Schottler et al. 2014). We have calibrated and validated a high resolution SWAT model to determine the ability of the model to reproduce hydrologic effects of agricultural drainage (Figure 10). In parallel, we have developed a reduced complexity hydrologic model with an empirical sediment production function to predict changes in sediment loading associated with increased or decreased future flow regimes. Remediation approaches, such as wetlands and land retirement have been proposed as solutions to reduce turbidity with the use of models such as SWAT (Gassman et al. 2007).

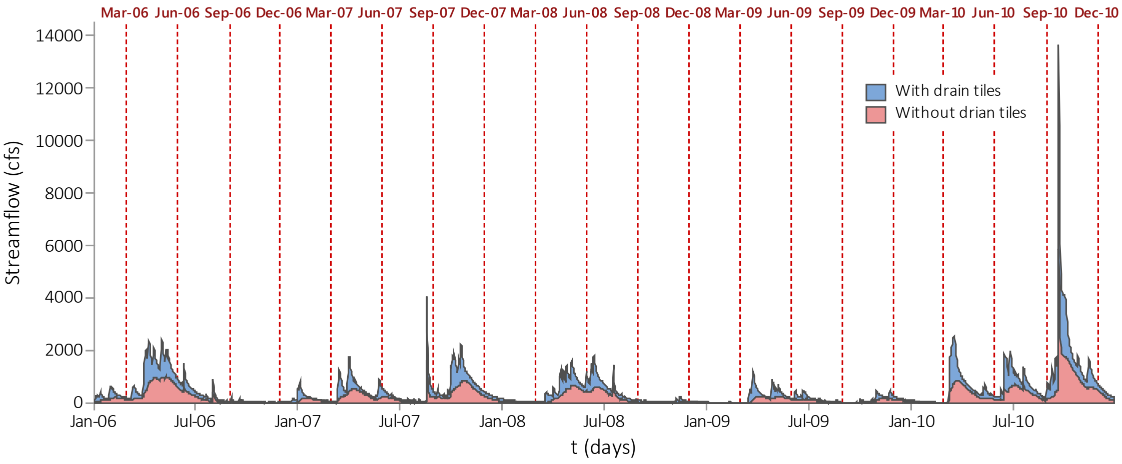


Figure 10. Stream flow outcomes predicted from SWAT considering no drain tiles and drain tiles for agricultural land with less than 2.5% slope.

We are also utilizing SWAT to demonstrate how multiple parameter combinations can result in similar outcomes, meaning completely different characterizations of a physical system can produce the same outcomes leading to variability in management and policy decisions (i.e., problem of model equifinality). Figure 11 shows the Nash Sutcliffe model evaluation criterion for 1200 SWAT model runs of the 2880 km^2 Le Sueur River Basin, with a simplified representation of land use to decrease computational demands. Results indicate that there are many parameter combinations that result in acceptable (> 0.5) to very good (>0.7) model calibration.

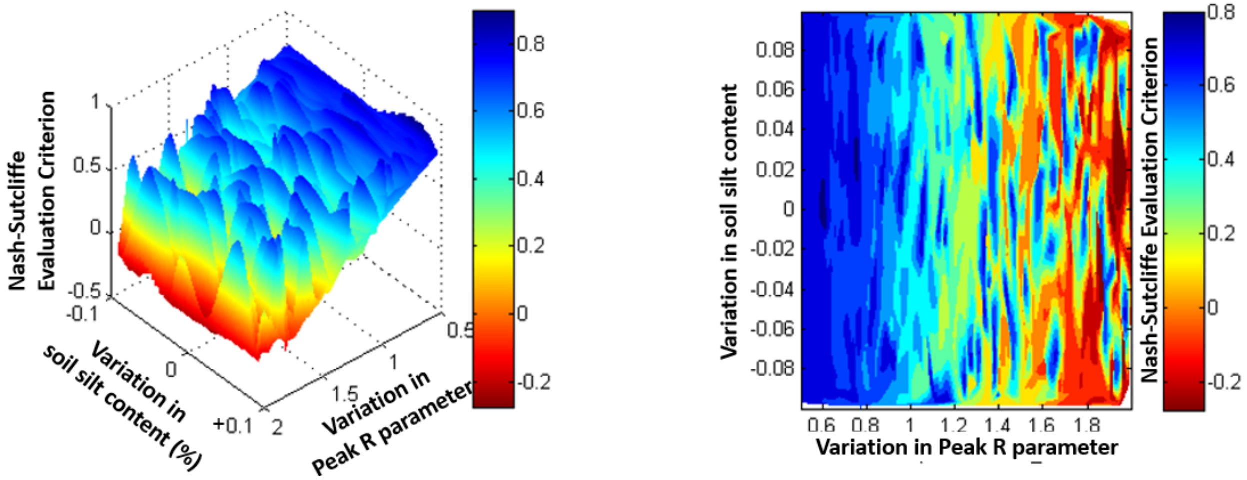


Figure 11. Nash Sutcliffe evaluation criteria resulting from 1200 model runs of SWAT for the 2800 km^2 Le Sueur River Basin. Six different hydrologic parameters, including silt content and Peak R parameter, were varied across reasonable ranges.

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Research Topics and Progress during 2014 - 2015

Economics group: Catherine Kling, Sergey Rabotyagov (faculty); Yongjie Ji (postdoctoral research associate); UW graduate students Zhengxin Lang and Nahyeon Bak

Brief summary of work

- **Land Use Modeling and Applications**

We extended last year's work on dynamic crop choice models with Iowa data into the four main areas in the Upper-Mississippi River Basin (which includes the Minnesota River Basin). In the crop choice framework, we consider forward-looking farmers who take crop system dynamics into consideration (rotational effects of corn-soybean crop system). The model is estimated econometrically using fine-resolution spatial data. The dynamic crop choice model is being used in two applications: water quality implications of land use change (crop choice) in different climate change scenarios and prediction of cover crops based on observational crop choice data. Currently, the water quality implication associating with land use change is analyzed based on the Environmental Policy Integrated Climate (EPIC) models. Integrating land use (crop choice) models with well calibrated SWAT model for Minnesota River Basin will be the next steps.

  - Dynamic Land Use Modeling and Water Quality Implications

Facing changing market incentives, farmers adjust their land use decisions (crop choice) accordingly to maximize profit. Since there are agronomic benefits from growing corn and soybeans in rotation, the crop choice decision is naturally dynamic; that is, when farmers decide to grow corn or soybeans they should rationally incorporate the impact of these decision on the profitability of future rotations. Several existing papers have linked land use decision models with water quality models to analyze the effects of land use change on water quality. However, these papers have employed simple, static models of land use change. In this work, we link an explicitly dynamic econometric model of crop choices with the Environmental Policy Integrated Climate (EPIC) model to analyze water quality implications in different scenarios. This work has two stages. The first stage is the estimation of dynamic discrete choice land use model, similar to DePinto and Nelson (2009), but using the estimation strategy proposed in Arcidiacono and Miller (2011). This land use model generates field-level spatial crop choice probabilities reflecting farmers' forward-looking behavior which are aggregated and incorporated into EPIC in the second stage. Two important policy scenarios have been analyzed. In the first scenario, the changes in land use and the consequences for downstream water quality associated with a permanent increase in corn prices relative to soybean prices were assessed. In the second set of scenarios, we examined the effects of climate change on water quality via land use (crop choice) change by using a set of regionally down- scaled future climate scenarios selected from a set of recent meteorological climate models. Briefly, the dynamic land use model capturing both forward-looking behavior and rotational effects have a better performance than the static model in modeling observed cropping patterns, and, for different policy scenarios, different modeling methods do give difference prediction in crop sequences. However, this difference manifests itself in minor modeled changes in nitrogen and phosphorus losses based on EPIC simulations.

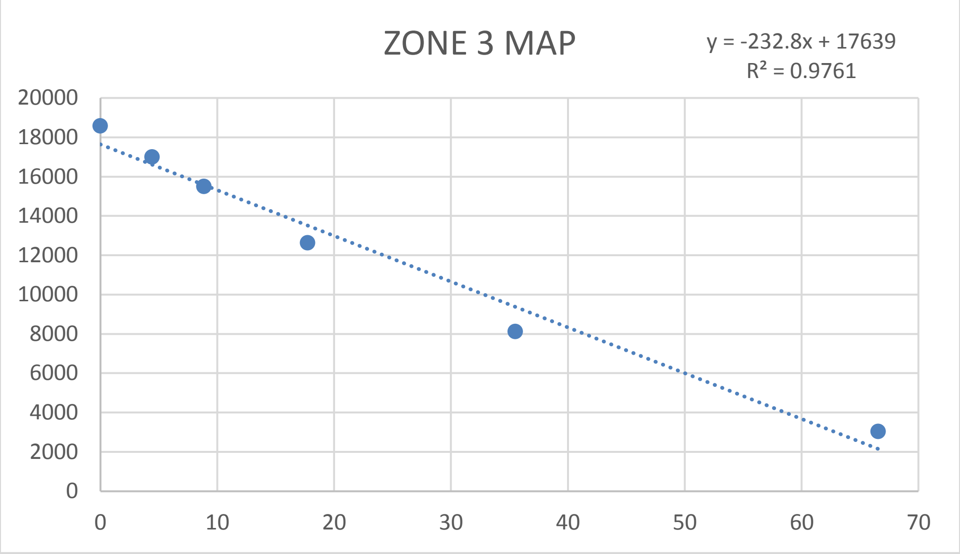
- Estimating Adoption of Cover Crops Using Preferences Revealed by a Dynamic Crop Choice Model

In this study, using a structural dynamic crop choice model, we build a framework to predict the adoption of cover crops and evaluate the subsequent water quality benefits in a number of future scenarios. Our proposed framework combines (1) a dynamic crop choice model, and (2) the use of relative change in revenues to reflect uncertainties associated with adoption of cover crops. With the spatially detailed land use data and other economic data from various sources, we have estimated a dynamic discrete choice crop choice model. The estimated coefficients are generally well expected and relative preferences for crop net revenues are in line with previous research. Based on the estimated parameters, we also extend the model framework to predict the choice probabilities of cover crops under a variety of scenarios. The primary results show relatively high predictions of probabilities to adopt cover crops under all scenarios. Although our results match quite closely the cover crop adoption rates presented in a recent survey (CTIC-SARE, 2014), they appear rather inflated when compared to USDA’s official Census of Agriculture state-wide estimates. Given that we place more confidence in the USDA Census estimates, we propose a calibration remedy based on readjusting the alternative specific constants associated with cover crop options to calibrate the model so that the base scenario probabilities match the observed share of cropland with cover crops in the NASS Census of Agriculture 2012 data. Using such aggregated data for field-level model calibration appears necessary prior to using results for policy analysis.

- **Spatial optimization of wetlands restoration: A case of Le Sueur Watershed in Minnesota River Basin**

  The Minnesota River Basin (MNRB) currently provides over 90% of Lake Pepin's sediment load, which adversely affects water quality, agricultural output and the ecological integrity of stream ecosystems. The function of wetland systems for the filtering and the treatment of sediments has been recognized by environmental engineers that specialize in the area of water purification. Constructed wetlands can reduce the peak flows of the rivers and then decrease the sediment loading rates according to the prediction results of Soil and Water Assessment Tool (SWAT). An ongoing study (Mitchell et al. 2014) shows that with 50% of total Water Retention Sites (WRS) area used in the Le Sueur Watershed, a sub-watershed of the MNRB in South-Central Minnesota, the predicted peak flow can be reduced by about 40%; while with 85% of WRS area used, the peak flow will be reduced by around 70%, and the sediment loading rate can be decreased by more than 75%. The goal of this work is to formulate a spatial optimization model for wetlands restoration to maximize sediment reduction in the Le Sueur Watershed, while also minimizing the total costs. The ongoing research by University of Minnesota will provide this project with spatial information and SWAT data with respect to peak flow and sediment reduction by wetlands. The area and location information of each WRS is available now. For the cost data, we use the data from Minnesota Farm Real Estate Sales as the opportunity cost for wetlands restoration. Both engineering cost and fixed cost will be estimated according to a wetlands restoration report from USDA (http://www.ers.usda.gov/media/1784721/err183.pdf). We start with a simple optimization problem (maximizing sediment reduction subject to a budget constraint) and build complexity into the decision by incorporating additional spatial constraints. Simple optimization results are being generated currently and the more complex spatial optimization program is being formulated using integer programming techniques.

Figure 1. A sample relationship developed between extent of artificial wetlands and mean annual sediment load in the Maple River of the LeSueur Watershed (underlying data provided by Nathaniel Mitchell). The coefficient on the linear trend represents marginal estimated annual sediment load reduction (in metric tons) due to a 1 km^2 increase in artificial wetland area and is used as a proxy for the sediment reduction benefit in spatial optimization.



- **Assessing farmer's crop choice and adoption of conservation technologies using a real options approach**

Recently, new agricultural conservation technologies including artificial wetlands, modified tile drainage and in-channel technologies (e.g., bluff stabilization) for improving water quality in agriculture-dominated watersheds have been introduced but these new practices have been slow to be adopted among farmers because of lack of incentives, especially in terms of farmers' revenue. In this work, we focus on farmers' decision on conservation practices by focusing on maximizing farmer's revenue over time under uncertainty. We find farmers' optimal choices on conservation practices which maximize their revenues including revenue from selling crops and from incentives for conservation practice adoption. In addition, we also show how uncertainties of revenue change the adoption of conservation practices. Given this kind of uncertainty in revenue, each year, farmers maximize their expected revenue by choosing between a continuous crop and rotation cropping system. In our preliminary simple model, the results show that crop rotation emerges as an optimal choice in a stochastic dynamic decision problem even when agronomic effects of crop rotation are not included in the model and due solely to optimal response to revenue uncertainty. Within the same stochastic dynamic optimization framework, we include the decision on whether to adopt new conservation practices which also introduce uncertainty in farmer's decision. This uncertainty can be direct, represented by uncertainty associated with a cost of adopting a new conservation technology, or uncertainty in benefits (stemming from either the purported private agronomic benefit or from a potentially uncertain government payment), or both. Indirect uncertainty can arise even when the engineering installation cost and benefit known with certainty, as farmers may be required to give up some private crop revenue, which is uncertain. We plan to develop this optimization model to calculate critical willingness to accept for adoption of conservation practices and find socially optimal policy schemes. In addition, we will also show how the optimal crop choice and adoption of conservation technology changes under various revenue paths, especially including unexpected intense shocks.

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Conference Papers and Presentations

1. Yongjie Ji, Sergey Rabotyagov and Catherine L. Kling. "Crop Choice, Rotational Effects and Water Quality Consequence in the Upper-Mississippi River Basin: Connecting Environmental Assessment Tools with a Dynamic Land Use Model" poster presented at the

2015 Annual Meeting of Association of Environmental and Resource Economics, San Diego, CA, June, 2015.

2. Yongjie Ji, Sergey Rabotyagov and Adriana Valcu-Lisman. "Estimating Adoption of Cover Crops Using Preference Revealed by a Dynamic Crop Choice Model" will be presented at the 2015 Annual Meeting of Agricultural and Applied Economics Association, San Francisco, CA, July, 2015.

Future Research (2015–2016)

1. Land Use Modeling with Different Land Use Datasets

In addition to the Cropland Data Layers, National Resource Inventory provides another rich set of historically, spatially detailed land use data. Due to different data collection methods and standards, these two data sets give different counts on local land use information. In this work, we intend to assess whether this discrepancy will generate significant economic implications under different land use modeling frameworks. A positive answer to this question would highlight the problem in a data-richer era about careful choosing an appropriate data set in their studies.

2. Modeling Conservation Practices with County Level Observational Data

Lack of spatially detailed observational data on farmers' adoption on conservation practices, such as cover crops, limits the prediction power of the crop choice model solely relying on observed crop choice data. With the 2012 Census of Agriculture, the first county level summary information about several conservational practices are reported, such as cover crops and no-tillage. In this study, we would use the BLP method (Berry et al, 1995), a widely used econometric method in the industry organization (IO) literature, to model this county-level data. This work will shed light on the relationship between the adoption of conservational practices at county level with other local factors, such as soil conditions, local weather patterns and local farmers' characteristics.

3. Further work on modeling adoption of conservation technologies using a real options approach

We plan to modify the existing model to investigate critical adoption thresholds using both "working land" (consistent with continued agricultural production) and "land retirement" (requiring foregoing agricultural production on all on fraction of land) agricultural conservation technologies. As described above, we will introduce both direct and indirect uncertainty into such decisions. In addition, we will also show how the optimal crop choice and adoption of conservation technology changes under various revenue paths, especially including unexpected intense shocks. Model results can provide optimization-based estimates of costs of adoption, which we expect to serve as inputs in spatial optimization work.

4. Incorporating Land Use Model and Real Options Model Results into Spatial Optimization

Previously, we developed simulation-optimization heuristics to efficiently allocate agricultural conservation activities across watersheds (using SWAT and evolutionary algorithms). One concern is that optimizing these kinds of systems is subject to exogenous shocks not under the control of a decision-maker or planner. Notably, weather or market shocks could have a significant impact on the efficacy and efficiency of solutions discovered. One concern is that a solution developed under one set of exogenous parameters (a climate regime, or a cropping pattern) may not be efficient under a different set of exogenous shocks. This is the lack of robustness concern (note that it's different from the concern that a distribution of exogenous shocks maps itself into the distribution of environmental outcomes and thus the attainment of any particular goal is fundamentally uncertain—concern over 'resilience' of solutions). Further note that the variation in exogenous factors can be large. We will continue building a robust optimization evolutionary algorithm which can 1) quantify the efficiency of a particular spatial solution with respect to exogenous shocks and 2) may increase the speed with which good approximations to optimal Pareto-frontiers are discovered. We expect to use estimates of costs of adoption from the real options model as inputs into optimization and the results of crop choice models as one dimension of exogenous shocks. The policy rationale is that one can expect that public control over conservation practices (or incentives for adopting such practices) is more likely that control over crop choices which is more likely to be influenced by broader market forces and agricultural policy at the national scale.

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

REACH (REsilience under Accelerated CHange)

Year 3 Research Summary for 2014–2015

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.

REACH principle investigators include:

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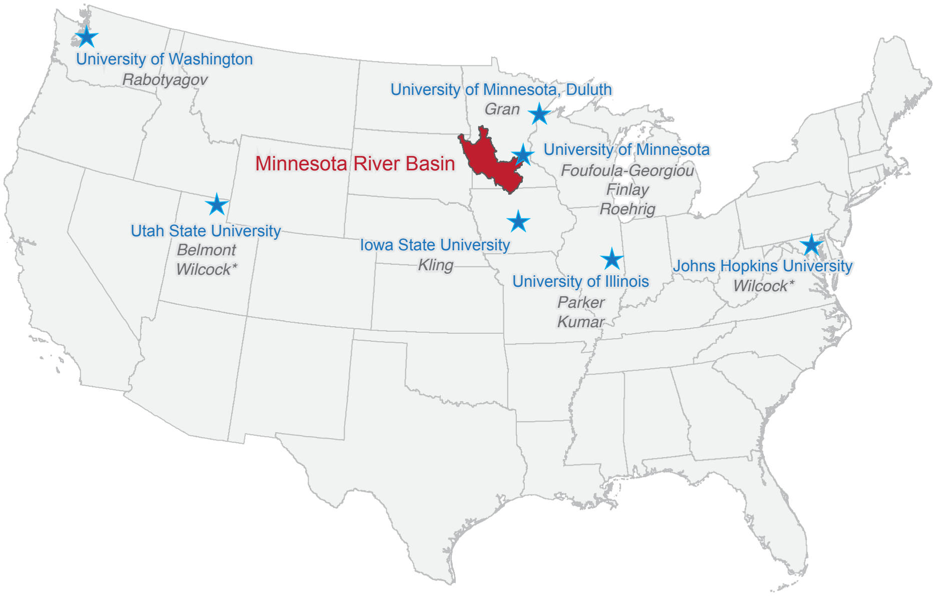
Catherine L. Kling – Iowa State University

Sergey Rabotyagov – University of Washington



Efi Foufoula–Georgiou's group:

Jonathan Czuba, Mohammad Danesh-Yazdi, Amy Hansen, Anthony Longjas,

Jon Schwenk, Zeinab Takbiri, and Alejandro Tejedor

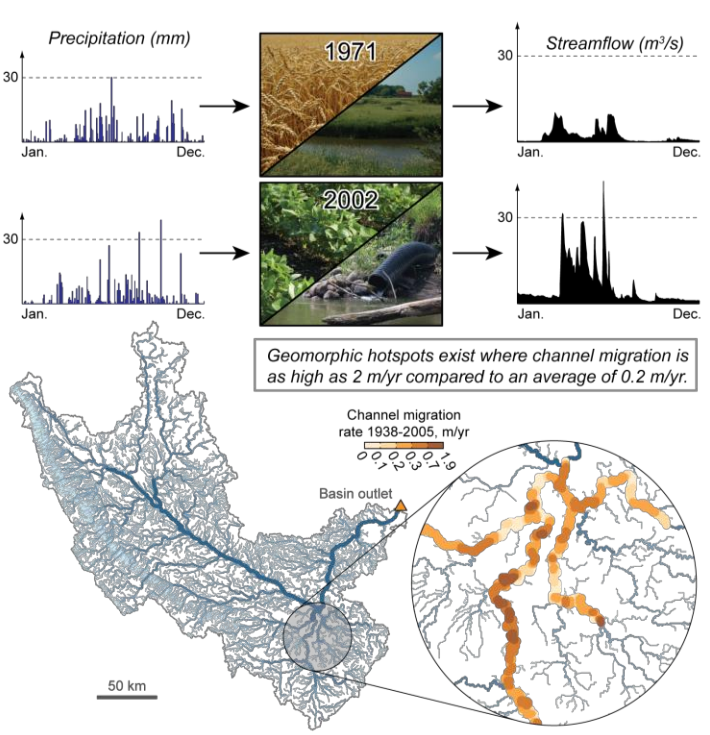
Research Themes and Accomplishments during 2014-2015

Our research efforts during the third year of the project continued on the overarching theme of understanding the hydro-geomorpho-ecological processes and feedbacks in an intensively managed agricultural landscape towards identifying vulnerabilities to change and informing management decisions. Specifically, our research concentrated on five main areas: (1) a network-based approach to river basin vulnerability assessment, (2) effect of agricultural drainage on hydrologic response, (3) expression of geologic controls on multi-scale river network structure, (4) meandering river dynamics, and (5) integrative predictive modeling of river hydro-geo-biological processes with emphasis on the effects of sediment change to riverine health. The developed frameworks and models, although general and transferable to other sites, were prototypes and tested in the Minnesota River Basin (MRB), which is the focus of the REsilience under Accelerated CHange (REACH) project funded under NSF's WSC program. We posit that such non-parametric analyses and reduced complexity modeling can provide more insight than highly parameterized models and can guide development of vulnerability assessment and integrated watershed management frameworks.

1. Network Approach to River Basin Vulnerability Assessment

Landscapes are too complex to be modeled with fully distributed deterministic models that consider all the small-scale physics and interactions and require as many as a hundred calibration parameters. Besides, changes in climate, land use, and water management impose non-stationary conditions, and nonlinearities in the system make it sensitive to uncertainties and small perturbations. Recognizing these limitations, we developed a simple network-based modeling framework [*Czuba and Foufoula-Georgiou*, 2014, 2015] that focuses on understanding and predicting the emergence of "hotspots of change" (Fig. 1) and captures the most important interactions and amplifications by exploring the system connectivity and its transport pathways including residence times, threshold behavior, and physical transformations.

The framework includes: (1) decomposing the landscape into a connected network of elements including river channels, wetlands, agricultural fields, etc., (2) spatially and temporally distributing inputs of water and sediment, and (3) tracking these inputs through individual landscape elements through process-based time delays. This framework has successfully identified vulnerable reaches of a river network prone to high rates of channel migration by highlighting where bed-material sediment has a tendency to persist and thereby encourage bank erosion [*Czuba and Foufoula-Georgiou*, 2015]. Furthermore, the framework has been used to unravel source contributions that synchronize on the network to form large clusters (i.e., areas of the network with high concentrations of flux) at channel migration hotspots (Fig. 2). Depending on network structure, process dynamics, and timing of arrival, the potential management options available may differ for reducing sediment generation of these specific source areas or for breaking the synchronization of these contributions before they coalesce into an aggregated mass. *By placing dynamical processes occurring at small scales into a network context using the dynamic connectivity framework, it is possible to better understand how reach-scale changes cascade into network-scale effects, useful for informing the large-scale consequences of local management actions*.



Geomorphic hotspots exist where channel migration is as high as 2 m/yr compared to an average of 0.2 m/yr.

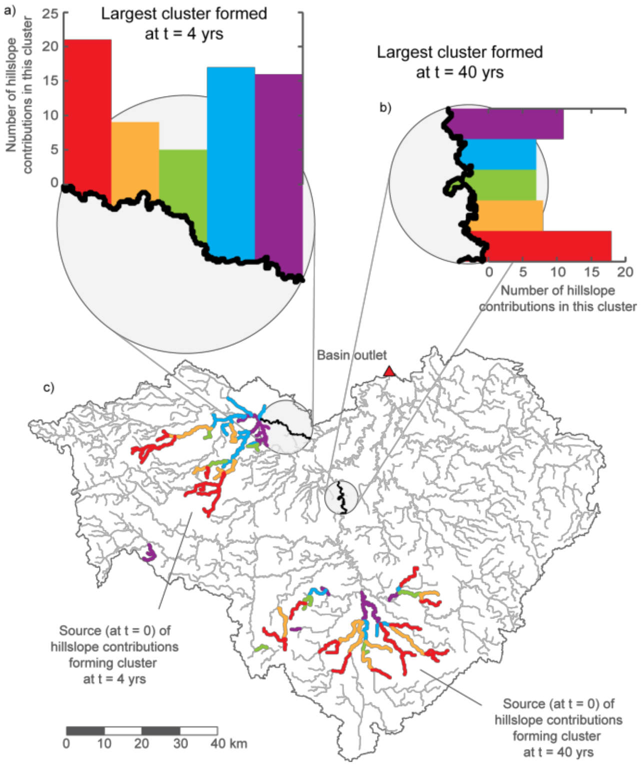


Figure 1. (Left) Agricultural land-use change has amplified streamflows in the MRB. Almost the same amount of precipitation in 1971 and 2002 resulted in a 3× increase in streamflow in 2002 (top). This amplification in streamflow is likely to concentrate physical, chemical, and biologic changes into "hotspots" (bottom), and the targeted management of these hotspots will most effectively improve the ecosystem.

Figure 2. (Right) Unraveling sediment sources that synchronize into "clusters" at locations of two channel migration hotspots. The largest cluster formed at time (a) 4 years (length ≈ 17 km) and (b) 40 years (length ≈ 15 km). The colored bars are the histogram of hillslope contributions within each cluster, where each color corresponds to a specific source area (at time 0) of the hillslope contributions composing the cluster, shown with the same colors in (c). This process-specific coarse-graining of the landscape allows the identification of space-time sources of sediment which eventually coalesce downstream due to the specific river network topology and flux dynamics.

2. Effect of Agricultural Drainage on Hydrologic Response

The hydrology of many agricultural landscapes around the world is changing in unprecedented ways due to the development of extensive surface and subsurface drainage systems to optimize productivity (Fig. 3). This plumbing of the landscape is altering water pathways, timing, and water losses creating new regimes of hydrologic response and driving a chain of environmental changes in sediment dynamics, nutrient cycling, and river ecology. Figure 3c demonstrates a pronounced spatial gradient in the progression of agricultural land-use change in the MRB. Agricultural transitions, defined as the year when the percentage of soybean cover exceeded that of hay and small grains as determined from the county level land use data (see Figures 3a-b), occurred from the late 1950s and early 1960s in the southeastern MRB to the 1990s and 2000s in the northwestern MRB. Studying the hydrology of basins which have already transitioned into a new agricultural regime is expected to provide much insight into the environmental future of the still-evolving basins.

We have proposed a framework to quantify the detailed nature of hydrologic change non-parametrically and study how this change might modulate ecological transitions [*Foufoula-Georgiou et al*., 2015]. Via time-frequency decomposition and a system's analysis approach of hydrograph slopes using Copulas, we quantify sharper rising limbs of daily streamflow hydrographs and stronger dependence on the previous-day precipitation, suggest a changed storage-discharge relationship, and show that the artificial landscape connectivity has most drastically affected the rainfall-runoff relationship at intermediate quantiles during the growing season (May-June) (Fig. 4).

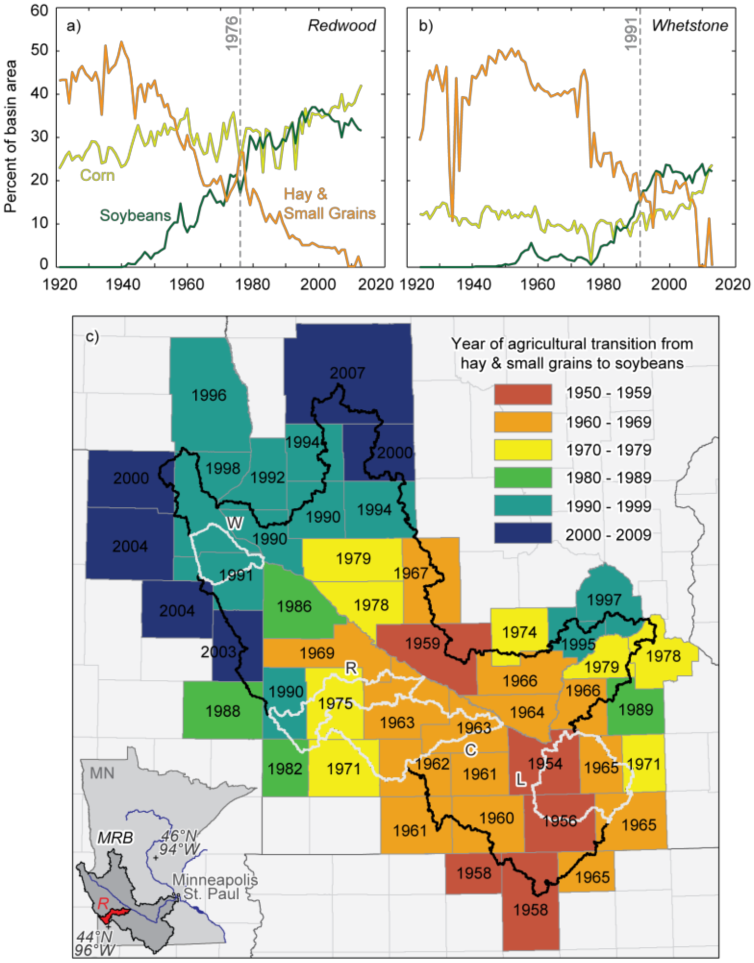
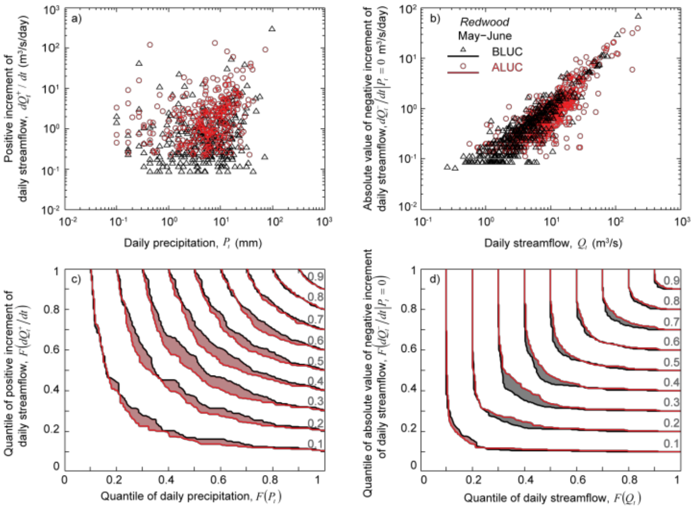


Figure 3. Temporal progression of agricultural changes in the MRB. The agricultural transition year is defined as the year when the percentage of the basin area for growing soybeans exceeded that for hay and small grains (barley, flax, oats, rye, and wheat) (see examples in (a) and (b) for the Redwood and Whetstone basins). The map of (c) demonstrates the southeastern to northwestern progression of this agricultural transition. The Redwood (R), Whetstone (W), Cottonwood (C), and Le Sueur (L) sub-basins are shown for reference.

Figure 4. Copula inter-quantile analysis of hydrologic response for the Before Land-Use Change (BLUC; black) and After LUC (ALUC; red) periods of the Redwood basin (where 1976 separates the two periods for analysis, see Fig. 3). (a) Scatterplot of positive slopes of daily hydrographs dQ_t^+/dt versus previous day precipitation P_t. (b) Scatterplot of negative slopes of daily hydrographs dQ_t^-/dt conditioned on no previous-day rainfall ($P_t = 0$) versus streamflow Q_t. (c) Copula of dQ_t^+/dt and P_t. (d) Copula of $dQ_t^-/dt \,|P_t = 0$ and Q_t. A strengthened dependence of streamflow increase to previous day rain (plots (a) and (c)) and a reduced dependence of the falling hydrograph slope to streamflow magnitude (plots (b) and (d)) is observed in the ALUC period.



3. Expression of Geologic Controls on Multi-Scale River Network Structure

External climatic or geologic controls, such as tectonics or glacial drainage, might impose constraints on landscape self-organization resulting in spatial patterns of rivers and valleys which do not obey the typical self-similar or self-affine relationships found in most landscapes. We have quantified how such geologic constraints might express themselves on channel network topology, spatial heterogeneity of drainage patterns, and emergence of preferred scales of landscape dissection. We used as an example the Headwaters River basin located in the upper MRB where successive glaciations have carved the landscape that has evolved over the past thousand years leading to a pronounced spatially anisotropic channel network structure which violates most scaling laws of fluvial landscapes [*Danesh-Yazdi et al., in preparation*]. Figure 5 illustrates the MRB and the geological feature called Coteau des Prairies (CDP) which was formed around 100,000-10,000 BP as a result of repeated glacial cycles covering the bedrock with glacial till deposits. It is seen how the channel dissection of those MRB sub-basins containing the CDP region differs drastically from the drainage pattern of typical landscapes, with persistence of quasi-periodic ridges and valleys and high channel density.

We found that typical Hortonian self-similarity tests are unable to detect the spatial heterogeneity in topology, while the stricter Tokunaga self-similarity test can reveal the irregularities present in the branching structure of these river networks. The length-area scaling and the probabilistic relationship between the slope and local drainage density also revealed how geologic constraints created a competition for space resulting in channel geometric and topographic properties different from those expected in typical landscapes. To identify the specific preferred scales of organization in such a landscape, multi-scale detrending via wavelets was used to successively remove scales of interest and examine how the variance of the detrended landscapes changed with scale. The analysis revealed a spectral gap at scales corresponding to the wavelengths of the quasi-periodic ridges and valleys present in CDP region (Fig. 6). *The ultimate scope of our study is to investigate how the multi-scale variability in landscapes depicts pronounced regularities (probably the result of an externally imposed control such as geology) that "break" away from the typical "cascade of energy" so familiar for landscapes that have evolved in the absence of external controls. The range of scales of this externally imposed "regularity" is then quantified and descriptions of the self-dissimilar network structures investigated to aid in the quantitative analysis of how fluxes in the basin depend on scale*.

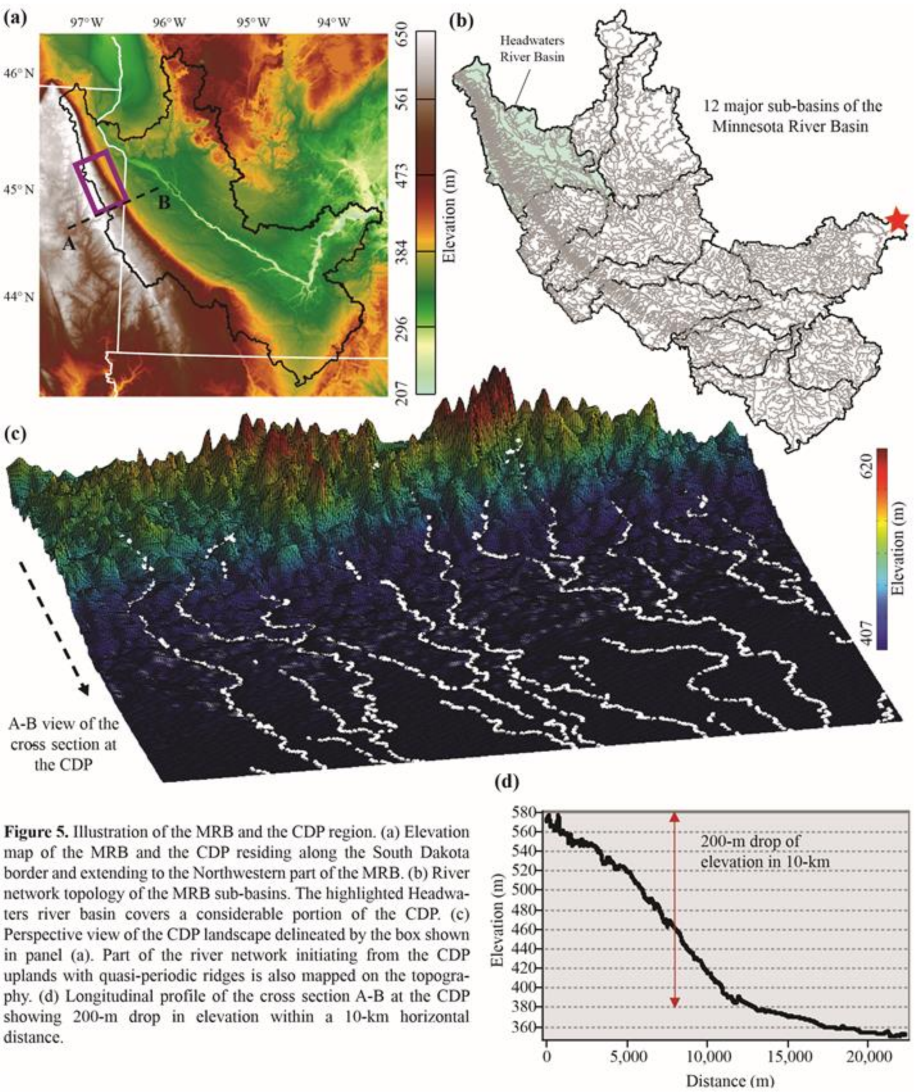


Figure 5. Illustration of the MRB and the CDP region. (a) Elevation map of the MRB and the CDP residing along the South Dakota border and extending to the Northwestern part of the MRB. (b) River network topology of the MRB sub-basins. The highlighted Headwaters river basin covers a considerable portion of the CDP. (c) Perspective view of the CDP landscape delineated by the box shown in panel (a). Part of the river network initiating from the CDP uplands with quasi-periodic ridges is also mapped on the topography. (d) Longitudinal profile of the cross section A-B at the CDP showing 200-m drop in elevation within a 10-km horizontal distance.

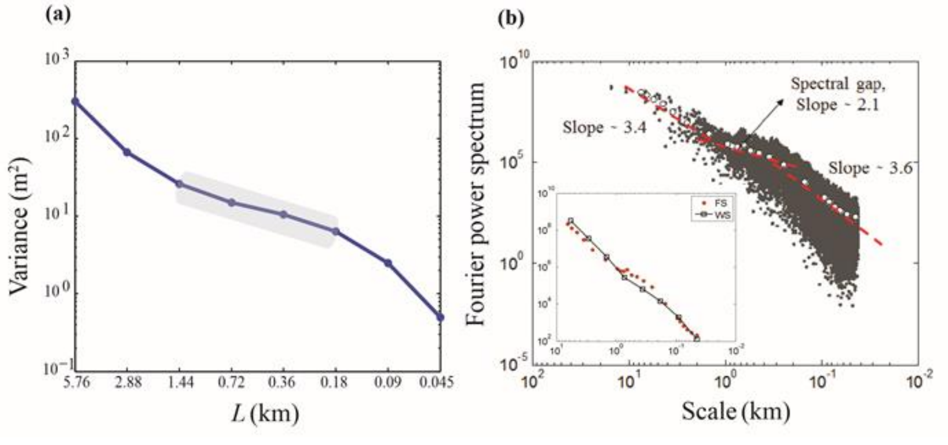


Figure 6. (a) Variance of the detrended landscape containing features smaller than L versus scale L. A reduced contribution to the overall variance is observed from features within scales of 0.18 km-1.44 km. (b) The Fourier and wavelet (indicated as inset) power spectra for the original landscape residing within the CDP region. The spectrum shows a spectral gap between scales ~ 0.3 km–1.5 km, which are close to the wavelengths of the quasi-periodic ridges and valleys present in this region as instigated by the large-scale geologic control of 14,000 years ago.

4. Meandering River Dynamics

Meandering rivers with high rates of channel migration can deliver large quantities of sediment to rivers, indirectly affect water quality and biotic functioning, and increase the risk to public and private property. In order to understand how, and ultimately predict where, a river channel will migrate, the challenge lies in linking the meander process to the sinuous river channel planform pattern. To this end we used numerical modeling to establish links between a meandering river's planform (i.e. shape) and its migration dynamics [*Schwenk et al*., 2015]. We found that the physically-based yet simplified model dynamics inherently produce a prototypical bend shape, dubbed *simple*. Cutoffs act as perturbations to the channel planform, resulting in a spectrum of bend geometries including two other archetypal geometries: *round* and *long* (Fig. 7b). Using three measures of bend migration, we showed that bends with similar cutoff geometries shared similar dynamic histories, enabling the inference of historic dynamics from static cutoff shapes. Specifically, *simples* migrated fastest and *longs* slowest with *rounds* showing significant variability in their dynamic trajectories.

Results of this work have both practical and theoretical implications. Inferring channel dynamics from static planform shapes is vital to understanding a river's dynamic past, especially in cases where no historic data are available, and aids in stratigraphic interpretation. If the Mississippi River in Minnesota were reasonably well-described by our model, aspects of its morphologic history could be estimated despite a lack of historic data through simple measurements of oxbow geometry (Fig. 8a). Furthermore, our analyses indicated that individual meander bends were most sensitive to perturbations early in their lives. This result may aid decision makers when considering dam and bridge constructions, dredging, and bank armoring.

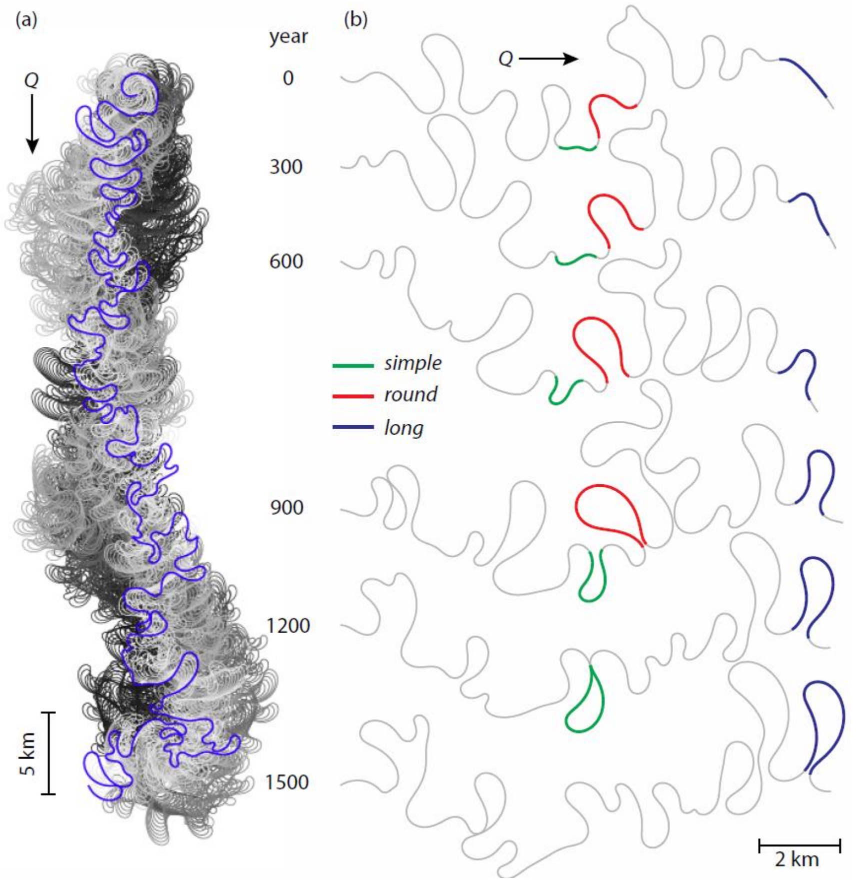


Figure 7. A long-term simulated meandering river. (a) 30,000 years of modeled centerline realizations. Older centerlines are darker; the blue centerline shows t = 30,000 years. The upstream boundary condition fixes the first centerline node in place, leading to the formation of the spiral pattern at the upstream boundary. No restrictions are placed on the downstream node so the river may migrate freely. (b) A reach of simulated centerline selected shows the growth and cutoff of three prototypical bend types that emerge from the physically-based deterministic model dynamics. Realizations are 300 years apart. Note the complex multilobe meander that starts as double lobed but develops a third lobe before cutting off between 900 and 1200 years.

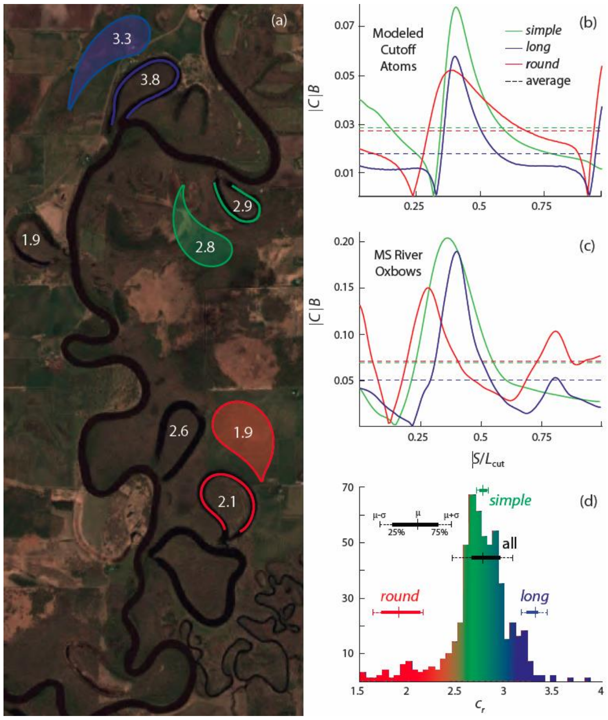


Figure 8. Geometric classification via curvature measures for modeled and real meander loops. (a) Aerial photo of a reach of the Mississippi River in Minnesota, USA. Centerlines of three oxbows have been traced in colors corresponding to the cutoff bend geometry they most resemble. The shaded meander loops are cutoff bends simulated by the model and are positioned next to similarly shaped oxbows. White numbers in the center of each oxbow or model bend are c_r values (ratio of apex curvature to average curvature). (b) Absolute value of curvature signals for the cutoff bends simulated by the model shown in (a). Dashed lines are average absolute curvatures. (b) Absolute value of curvature signals for the traced oxbow lakes of the Mississippi River shown in (a). (c) The distribution of c_r simulated by the model shows how c_r serves as a good metric for ordering meander loops of various geometries by shape. The color gradient of the c_r histogram emphasizes that simulated bend shapes are characterized by a spectrum rather than falling neatly into one of the three archetypal shape (*simple, round, long*) categories. Statistics for each group have sample size n=25, while n=552 for all cutoff bends. The c_r mean value for all cutoff bends is 2.77. Map data: *Google Earth: DigitalGlobe*. 46◦37’31.36”N, 93◦38’13.31”W. Imagery date 7/2/2011.

5. Integrative Hydro-Geo-Biological Predictive Modeling

Freshwater fauna have dramatically declined in both diversity and abundance worldwide concurrent with changes in streamflow and sediment loads in rivers. To understand how cumulative effects and interdependency of chronic environmental stressors, e.g. high suspended sediment concentrations and phytoplankton (food) limitations, may affect population dynamics of long lived organisms, such as freshwater mussels, a simplified dynamic interaction model that couples hydrology to river ecology (Fig. 9) was developed [*Hansen et al*., 2015]. Using this model we demonstrated how the observed hydrologic change and/or the water-driven sediment generation dynamics may modulate a regime shift in river ecology, namely extirpation of native mussel populations, at several sites in the MRB [*Foufoula-Georgiou et al*., 2015]. Such analysis can be useful in guiding possible remediation strategies, as briefly illustrated below.

Observed mussel population density at the Redwood site is among the lowest in the MRB (Fig. 9c). We simulated mussel population densities across a range of realistic sediment generation (α,β values in Fig. 9b) using repeated Before Land-Use Change (BLUC) or After LUC (ALUC) (see Fig. 3) streamflows until populations reached a steady state (Fig. 10a). The resulting α,β space can then be divided by a line demarcating the critical threshold for a regime transition that is determined by the applied hydrology; above this line, populations are extirpated and below this line, populations reach their effective carrying capacity. This space for the Redwood site (Figure 10b) tells a compelling story. Conservatively consider that sediment generation has remained constant across both BLUC and ALUC periods (gray “+” symbol). In this case, altered hydrology via streamflow alone was sufficient to switch the population to extirpation. If, on the other hand, sediment generation did change along with hydrology (black triangle for BLUC, red circle for ALUC), the respective α,β are farther from the regime transition line in both BLUC and ALUC periods, indicating an even more drastic change in the rate at which the populations approach steady state. In either case of altered hydrology or altered sediment production, a population growing toward its effective carrying capacity in BLUC conditions declines toward extirpation under ALUC conditions.

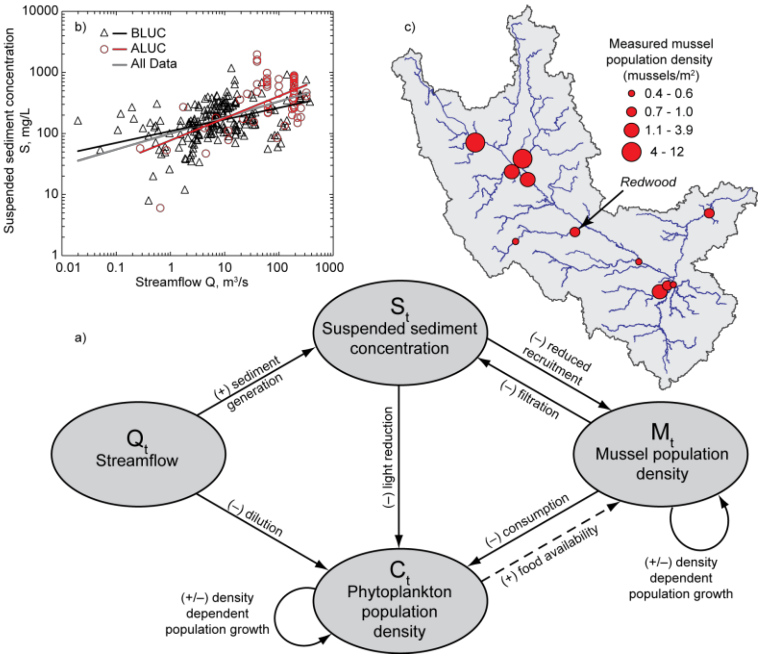


Figure 9. Overview of simulated mussel population dynamics driven by streamflow. (a) Schematic of the process interaction network showing the couplings incorporated in the mussel population density model. Each arrow represents a physical interaction considered by the model which is either positive (+) or negative (-). (b) Flow-sediment relationship from USGS gaging station data with power law fits for BLUC (n=207), ALUC (n=67), and all data. *α, β* values for each period: BLUC (29.1, 0.191), ALUC (6.36, 0.362), and all data (16.4, 0.262). (c) Map of the Minnesota River basin showing the sites (red circles) with observed mussel population densities where the model of *Hansen et al*. [2015] was applied. A detailed analysis of model dynamics focuses on the Redwood site indicated by the arrow.

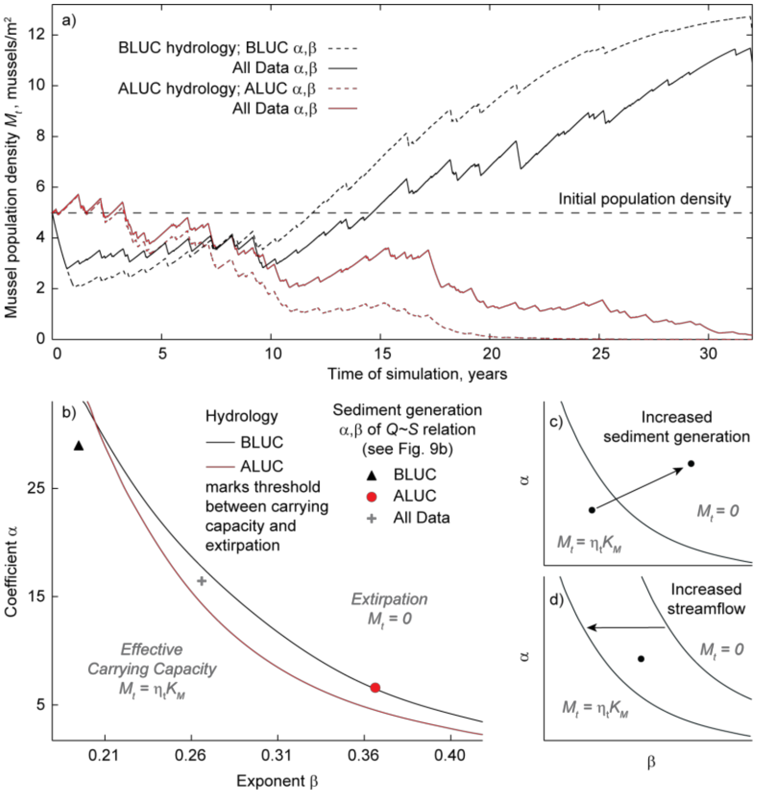


Figure 10. Mussel population stability as a function of hydrology and sediment generation. (a) Mussel population densities are simulated for 32 years driven by hydrology Before Land Use Change (BLUC; black lines) and After LUC (ALUC; red lines) (see related Fig. 3 and 4). For each hydrology, populations were simulated using the flow-sediment relationship of the respective period (dashed lines) and the relationship derived from the entire record (solid lines). (b) Population stability diagram for the Redwood site. Regime transition lines depend on observed hydrology, while positioning in the space depends on the (*α,β*) fits to observed data (Fig. 9b). Points above a given line correspond to (*α,β*) pairs that result in extirpation as the stable fixed point, while those below have a stable fixed point at the effective carrying capacity. Points far away from the line reach steady state faster than those nearer the line (see (a)) (c) Fixed point stability may switch due to changes in sediment generation or (d) changes in hydrology.

Future Research (2015–2016)

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

1. Network Approach to River Basin Vulnerability Assessment.

- Relax some of the assumptions of the network-based sediment transport framework to include storage and space-time variable release of sediment in the system.
- Use this framework to investigate management actions and vulnerability/resilience questions to future changes in the MRB.
- Extend the network-based model to include water retention basins for modeling nutrient and fine sediment transport in a watershed to guide mitigation and planning strategies, i.e., where and with what properties to locate retention basins for achieving desired objectives.

2. Effect of Agricultural Drainage on Hydrologic Response

- Further quantify the effect of tile drainage on the basin hydrologic response at multiple temporal scales (daily up to weekly) by performing analysis of several sub-basins within the MRB and relating the results to land use change.
- Understand how the hydrologic response change depends on spatial scale (plot to large watershed scale) via coupling a response function model with a network transport model.
- Use a travel time distribution approach and available data of nutrients or other tracers to understand the storage function of the pre-development and post-development landscapes and assess whether such a systems level approach to watershed modeling can be useful for management and planning.

3. Expression of Geologic Controls on Multi-Scale River Network Structure

- Understand how river networks not obeying the typical self-similar structure can be modeled via extended forms of higher-order branching structure topologies.
- Investigate more closely the break of self-similarity and its physical causes in other sub-basins within the MRB.
- Explore how topologic self-dissimilarity projects itself into a break in the scaling of mean annual and maximum annual peak streamflows with upstream contributing area.

4. Meandering River Dynamics

- Test the connections found between simulated planform geometries and migration dynamics using real data from Landsat imagery – for this, one of the most rapidly migrating rivers of the world (Ucayali River in Peru) has been selected for analysis.
- Further understand how natural meander migration is affected by constraints imposed by human factors and how these external perturbations propagate throughout the system to change the dynamics of meander growth and cut-offs.
- Evaluate the performance of a suite of meander migration models of various complexities by comparing dynamic trajectories of real river bends.
- Probe the inherent nonlinear dynamics in meandering river planforms and dynamics using tools from nonlinear dynamical theory to better understand sensitivity to future perturbations.

5. Integrative Hydro-Geo-Biological Predictive Modeling

- Theoretically study the non-linear dynamics and threshold behavior (two states of attraction) of the developed hydrologic-ecologic model and understand what parameters or model component parameterizations mostly control the long-term behavior.
- Perform a more extensive sensitivity analysis to unknown or poorly estimated parameters to pinpoint what quantities need to be known in a basin to be able to accurately predict the water-sediment-mussel population density continuum.
- Use the model as a tool to suggest management scenarios in a basin that might allow declining mussel populations to rebound and avoid further decline toward an extinction threshold.

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Research update

Like many human dominated watersheds, excess sediment, nitrogen, phosphorus, and water are the major drivers of water quality degradation and biological impairment in the Minnesota River Basin (MRB). Impairment of MRB streams and lakes exceed that of many other Midwestern watersheds, and therefore serve as an important example of disproportionately large impacts of one watershed on regional water quality. The extreme conditions in the MRB arise from complex interactions of geological history, land use, and climate change. Our research assesses landscape and climate change drivers of stream biogeochemistry, biological structure, and ecosystem processes in agriculturally dominated watersheds studied in the REACH framework. We are using data synthesis, modeling, and GIS to identify controls of watershed nutrient export through leveraging analyses of existing databases. With new data collection efforts, we are examining relationships between river network physical structure and biological processes to inform predictive modeling of nutrient transport and cycling, and food web structure in highly dynamic landscapes. We focus intensively on understanding the influence of wetlands, lakes and riparian zones on local and downstream structure and processes in stream networks, and legacy nutrients. Research described below is in early to mid stages of implementation, with emphasis on activities from summer 2014. The empirical information we are generating and synthesizing from monitoring programs is gathered with a goal for integration and validation of several modeling efforts, many described elsewhere in this report.

1. Large Watershed Nutrient Mass Balance Analyses

We are analyzing annual watershed loading data and building nutrient mass balances to identify factors that lead to nutrient retention or stream losses in southern Minnesota (MN). We calculated nitrogen (N) retention for 57 watersheds in MN using estimates of Net Anthropogenic Nitrogen Inputs (NANI) and annual nutrient loads calculated by the Minnesota Pollution Control Agency and Metropolitan Council using methods described previously [*Howarth et al*., 1996; *Boyer et al*., 2002]. N retention includes N taken up on the landscape or denitrified into gaseous forms, and not released to streams and rivers. Annual loads for 2007-2011 were averaged, incorporating substantial variation in runoff. Sites spanned a gradient of urban, agricultural, forested, and wetland dominated land cover. Highly agricultural watersheds (>25% cropland) have high N inputs, but N retention is highly variable between sites. N retention decreases with greater N inputs (Fig. 11; $n=39$, $R^2= 0.28$, $p<0.001$). Greater runoff and average annual precipitation are associated with lower N retention and greater wetland and lake cover are associated with higher N retention. N retention at highly agricultural sites is best described with a multiple regression including precipitation, crop cover, and lake cover ($n = 35$, $R^2 = 0.68$, $p<0.001$). Thus, variation in precipitation and land use intensity are important to determining how much N is taken up or denitrified in watersheds. Additionally, lakes and wetlands in agricultural areas are important sinks for inorganic N.

Plans for next year: Net Anthropogenic Phosphorus Input (NAPI) calculations are ongoing and will be used with watershed phosphorus (P) loading data to analyze factors that regulate P retention across watersheds. Examination of interannual variability in N and P export driven by climate is planned using the multi watershed database described above, as well as analysis of the factors controlling the specific forms of N and P exported (i.e. organic vs. inorganic nitrogen, and dissolved vs. particulate P).

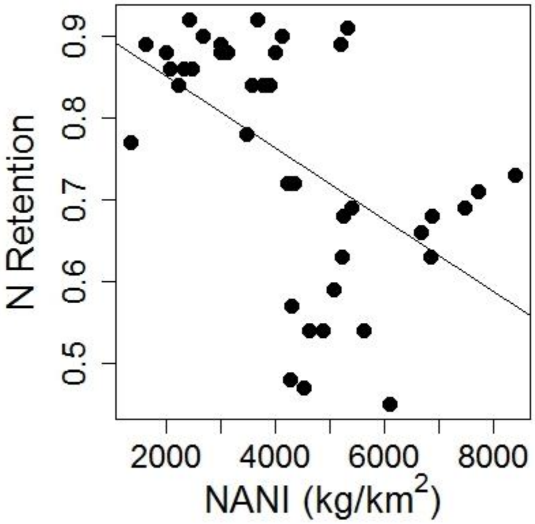


Figure 11. Annual watershed nitrogen (N) retention decreases with greater N inputs in highly agricultural watersheds. N loss to rivers (i.e. lower retention) under higher NANI conditions is related to higher watershed runoff, and lower losses (i.e. higher retention) is related to extensive coverage by lakes and wetlands, which serve as sinks for NO_3 leached from farm fields.

2. Sources, sinks, and controls of nitrogen and phosphorus in the Le Sueur River

The MRB is a major source of N and P to the Upper Mississippi River, and a relatively small part of the basin contributes the majority of nutrient loadings. The Le Sueur River watershed is representative of a “hotspot” for high nutrient export and poor water quality which impairs local and downstream biotic conditions and ecosystem services. This watershed is a focal area for much of our field research to understand sources and sinks for nutrients, and the interactions of climate and human actions that affect N and P.

Nitrogen: Stream nitrogen concentrations and loads peak during spring time conditions in the MRB, similar to other Midwestern watersheds. Record rainfall was observed during spring for much of MN during 2014. Despite the high water conditions, which can rapidly flush nutrients to large rivers without incorporation into plants, we observed signification retention of nitrogen in lakes and remnant wetlands. For example, across 94 sites sampled in one week in June and again in one week in August in three MRB HUC-8 basins dominated by crop cover with watershed areas ranging from 3 to 5,800 km^2 a significant negative relationship between nitrate concentration and percentage of drainage area that is wetlands or lakes was observed (Fig. 12). No relationship was seen between nitrate concentration and drainage area. Sampling through time at ten sites with drainage areas ranging from 0.5 to 20 km^2 and a range in extent of wetland cover showed that remaining wetlands suppress current N losses in the spring time period (Fig. 12). In addition to providing strong sinks for NO_3, lakes and remnant wetlands also increase levels of dissolved organic carbon (DOC) in stream water, which may enhance denitrification downstream (Fig. 13). These data suggest that small to modest increases in wetland cover could have strong positive impacts on N retention.

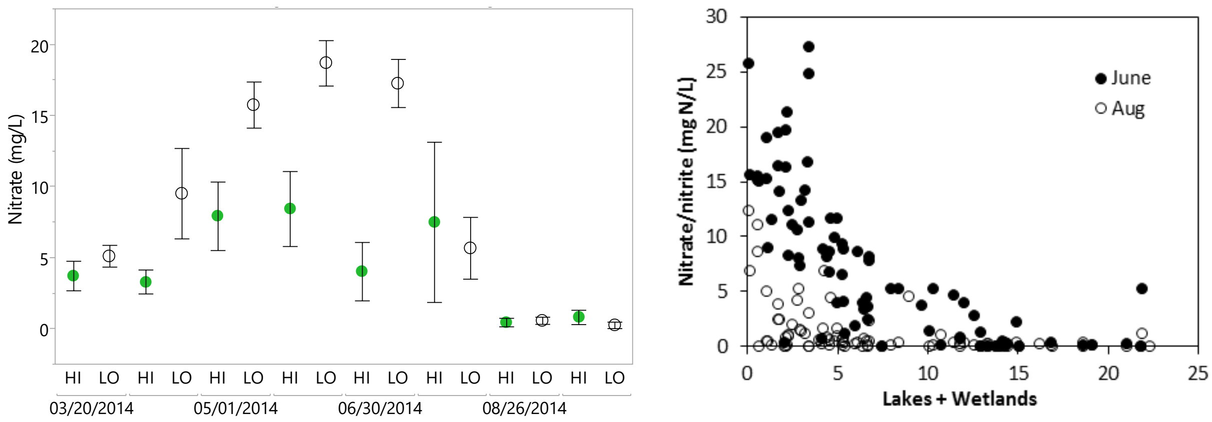


Figure 12. Temporal (left) and spatial (right) patterns of stream water nitrate/nitrite concentrations as measured in the Minnesota River Basin in 2014. Upstream wetlands and lakes decrease nitrate concentrations in receiving agricultural ditches during the critical spring loading period of April – June. Green closed circles are mean concentrations in ditches with > 5% wetland or lake coverage of their drainage area and open circles represent sites with < 5% wetland or lake coverage. Figure on right shows nitrate concentrations measured at ~90 locations in 3 sub-basins of the MRB at two time periods; one in June and one in August.

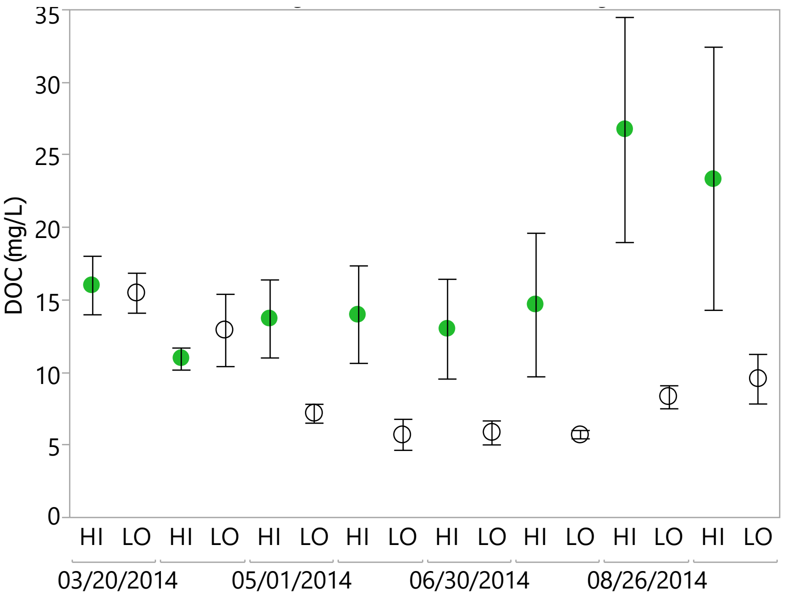


Figure 13. Upstream wetlands and lakes enhance the availability of carbon, in the form of DOC in agricultural ditches during most of the growing season. In early spring (March and April) ditch DOC is relatively high regardless of the presence of wetlands. Green closed circles are mean concentrations in ditches with > 5% wetland or lake coverage of their drainage area and open circles represent sites with < 5% wetland or lake coverage. Each point is the mean concentration for 5 locations. Errors bar represents one standard error from the mean.

Phosphorus: Excess phosphorus in streams, lakes, and rivers causes widespread impairment of water quality and habitat for biota throughout Minnesota, and much of the Midwest. While progress has been made in reducing P losses from sewage and field erosion sources, many waterways remain highly eutrophic. We are using intensive sampling and modeling to understand the source of P losses from the Le Sueur Basin toward identification of strategies that will be most efficient and effective for improving P retention. This work was not originally proposed and is leveraged via new funding from the Minnesota Department of Agriculture (MDA). Intensive sampling of the Le Sueur and two other agricultural watersheds, combined with analyses of state datasets (see previous section) show that soluble P dominates the total P concentrations and annual loads at a majority of sites. Soluble and particulate P appears to have different sources in the landscape. Soluble P levels often peak at snowmelt, but remain elevated throughout many agricultural drainage networks throughout the year. Particulate P levels are closely related to total suspended solids (TSS) concentrations, and have two major sources: lakes and bank erosion. Lakes strongly increase particulate P, reducing soluble P levels, and often function as hotspots for total P transport into rivers. Erosion of stream banks and bluffs is also an import source of particulate P in some watersheds, including our focal study sites in the Greater Blue Earth River Watershed. Ongoing work will relate sediment budgets developed within this and related projects to P budgets. Several modeling approaches, including SWAT, will be compared toward an integrated understanding all P sources and environmental controls in order to develop strategies for phosphorus management.

3. Patterns and processes effecting biotic structure in agricultural drainage networks.

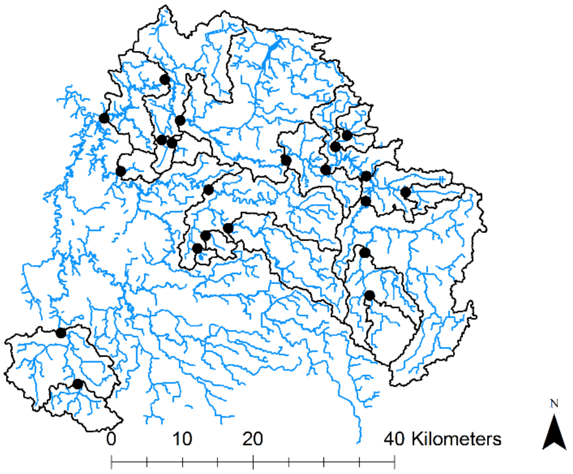
A holistic management approach to water quality challenges in the MRB depends on eliciting the linkages between physical processes, such as hydrology and sediment transport, and biological processes, such as the structure and function of river food webs and the sources of carbon that support them. Organic matter dynamics in streams and rivers – i.e., inputs, local production, storage, assimilation, and transport – are governed by flow conditions and related drivers, including climate, geology, and human land use [*Humphries et al*., 2014]. During times of rising flows, for example, rivers are often characterized by the longitudinal transport of material and energy from upstream allochthonous sources; at low flow conditions, by contrast, local autochthonous and local allochthonous inputs are thought to predominate [*Humphries et al*., 2014]. These variations in organic matter inputs and transport likely have important consequences for ecosystem processes and biota. Indeed, patterns in the variability and predictability of flow conditions and organic matter availability acting over very long time scales may represent strong evolutionary forces that shape life history strategies of many types of aquatic life, including plants, aquatic insects, and fish [e.g., *Winemiller and Rose,* 1992].

Filter-feeding and collecting macroinvertebrates are two groups of stream biota that feed on suspended and deposited particulate organic matter, respectively [*Wallace and Webster*, 1996]. The growth of these groups may therefore reflect dynamics in organic matter production, storage, and transport that stem from hydrogeologic drivers. For example, depending on ambient conditions and the specific taxa in question, filter feeding invertebrates may rely on suspended particulate organic matter (POM) from a number of different sources, including instream primary production (e.g., phytoplankton), processed allochthonous inputs from riparian vegetation or watershed sources (i.e., leaf litter), mobilization and transport of benthic organic matter, or soil organic matter washed from stream banks or watershed sources [*Wallace and Webster*, 1996; *Sheih*, 2002]. The growth and production of these feeding groups may subsequently propagate throughout river food webs, by affecting the quantity and type of POM in suspension, or by altering the structure of local benthic communities [*Wallace and Webster*, 1996].

Primary water quality concerns stemming from the intersection of human- and climate driven change in the MRB are excess sediment and nutrients [*MPCA*, 2015]. Suspended sediments are often considered detrimental to instream primary production, as sediments can both block light penetration to the stream and physically abrade instream macrophytes and algae [*Wood and Armitage*, 1997; *Henley et al*., 2000]. At the same time, however, excess nutrient levels in streams and rivers of the MRB can result in high levels of algal production at low flows. Thus, the nature of the relationship between suspended sediments, nutrients, and the production and transport of organic matter that represent potential food resources for macroinvertebrates is complex.

With this research, we are investigating variability in biodiversity, food sources and food web structure across stream networks, from upstream drainage ditches to downstream rivers, and across seasonal differences in flow, water chemistry, organic matter availability, and suspended sediments. Macroinvertebrate, water chemistry, and organic matter samples collected from the Le Sueur River basin in 2013 and 2014, together with additional prospective data to be collected in 2015 (Fig. 14), is being analyzed to address a number of hypotheses related to this objective.

Figure 14. Study sites and contributing watersheds in the Le Sueur River basin from which macroinvertebrates and sources of organic matter were collected for stable isotope analysis.



For example, we hypothesize that, in spring and early summer, filter feeders will consume fine particulate matter derived from benthic or soil stores, but will increasingly rely on organic matter derived from planktonic algae as the summer season progresses. Preliminary data from the Le Sueur River basin indicates that suspended POM in spring and early summer may derive from multiple sources, including soil organic matter, whereas POM in late summer is derived largely from instream primary production throughout the stream network (Fig. 15).

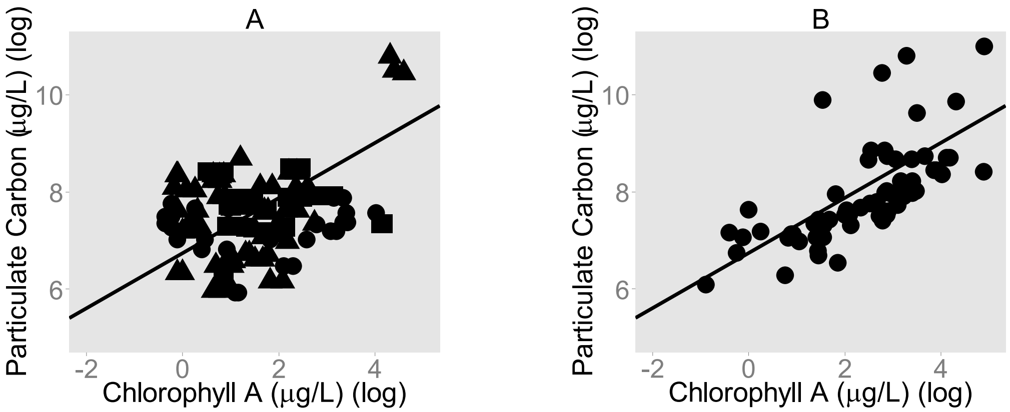


Figure 15. Particulate organic carbon as a function of chlorophyll concentrations in the Le Sueur River basin, in a) May-July, and b) August. Symbols indicate month of sample collection: cross=May, square=June, triangle=July, circle=August. The lack of relationship between chlorophyll and POC in May-July suggests that suspended carbon may derive from multiple sources in early- to mid-summer. The correlation between chlorophyll and POC in August indicates that suspended organic matter is largely derived from sources of instream primary production – i.e., phytoplankton-- in late summer (i.e., at lower flows).

A second aspect of this research is to couple an understanding of N and P sources and sinks (from Objective 2 above) to patterns in fish and macroinvertebrate biodiversity. This effort will leverage extensive biomonitoring datasets collected by MPCA and MN DNR to understand how landscape influences such as wetland cover may mediate relationships between stressors, such as excess nitrogen, and stream and river biodiversity.

Finally, we have sought to leverage the interdisciplinary partnerships fostered within the REACH group by proposing additional research, prospectively funded by the U.S. Environmental Protection Agency, which would integrate hydrological, ecological, and economic models at common spatial and temporal scales to understand the economic benefits of nutrient management conservation scenarios in the Upper Mississippi River basin (including the MRB). Designed in collaboration with Dr. Cathy Kling (another REACH PI) from Iowa State University, the objectives of this proposed research are to, 1) develop statistical ecological models to forecast the effects of watershed-scale conservation practices on the distribution of biodiversity (fish and aquatic insects) in streams and rivers of the Upper Mississippi River Basin (UMRB); 2) translate changes in biodiversity into ecosystem goods and services, and quantify their economic value using state-of-the-art revealed preference surveys and field experiments conducted with residents from a wide range of ecological and socio-economic conditions in the UMRB.

4. Watershed Scale Hydrologic Modeling

Efforts linked to watershed scale modeling of the Minnesota River Basin have focused primarily on improving the quality of the precipitation input data that have been used to inform the model. Previous model precipitation inputs have been based on either (1) volunteer observer stations, or (2) the Climate Forecast System Reanalysis (CFSR) data from the National Centers for Environmental Prediction. The CFSR data are generally an improvement over the volunteer observer stations because they provide uniform spatial coverage with no data gaps. However, with a grid resolution of approximately 38 km, the CFSR data may still be too coarse to capture intense but localized convective thunderstorms that are common during the summer in the upper Midwestern U.S.

More recently, precipitation data sets derived from NEXRAD radar data have presented another option for generating model inputs. These data are available from 2002 onward and offer near-continuous spatial coverage for the continental U.S. The data are not available in a format that is easily prepared for use by the SWAT model and require additional processing to identify missing data and fill in gaps from nearby grid points via interpolation. However, the final data product is a virtual network of rain gauges with a 4 km grid resolution. SWAT model weather inputs now rely on NEXRAD for precipitation and CFSR data for remaining inputs (temperature, solar radiation, relative humidity, wind speed). These inputs have improved model performance (Fig. 16), and preliminary calibration results show good agreement for key tributaries of the Minnesota River Basin. Ongoing calibration efforts are currently focused on improving flow agreement during the receding hydrograph limb of flow events.

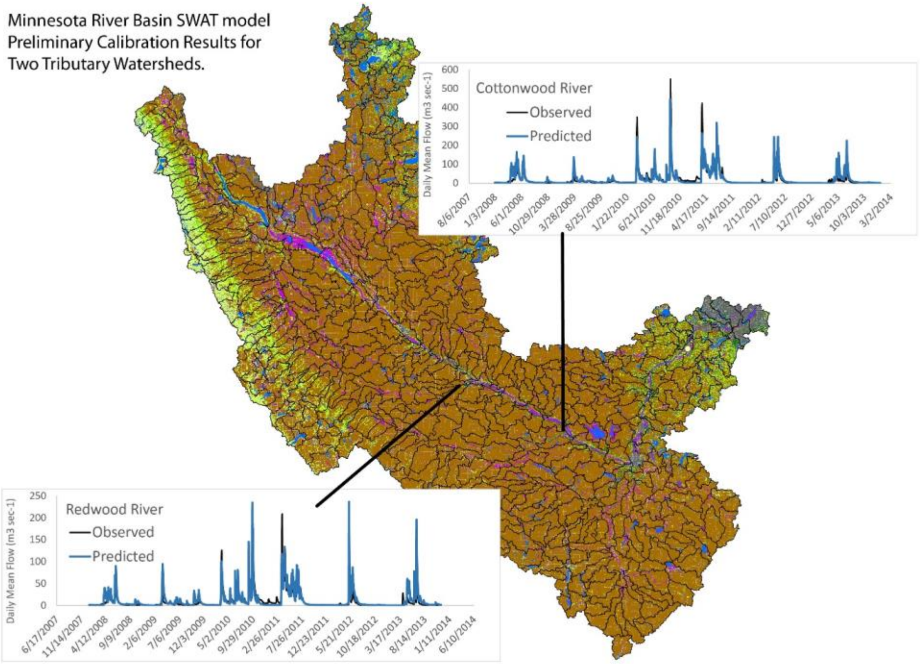


Figure 16. Preliminary hydrology calibration results from the SWAT model for the Cottonwood River Basin (3,367 km^2) and the Redwood River Basin (1,629 km^2).

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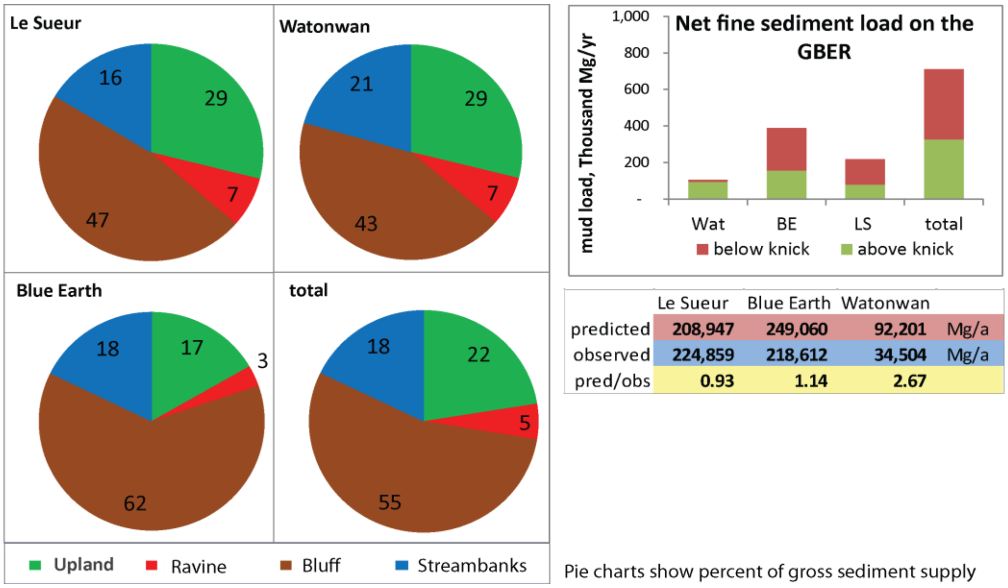
1. Understanding Sediment Sources in the Greater Blue Earth River Basin

Students: Martin Bevis (M.S. UMD 2015)

Main Collaborators: Peter Wilcock (USU), Patrick Belmont (USU), Stephanie Day (NDSU)

As a system under stress for high suspended sediment loads, there is a desire to understand sediment sources, pathways, and depositional sinks in the Minnesota River basin as well as develop an understanding of how the underlying geology and geomorphic history affect suspended sediment loading. We completed suspended sediment budgets for the Blue Earth and Watonwan Rivers in 2014, expanding upon a sediment budget already completed in the Le Sueur. Together, these budgets yield insights into how geology affects erosion and sediment loading in the Greater Blue Earth River basin.

About half of the GBER fine sediment load is sourced below knickpoints, a result of late Pleistocene base level fall. In the watershed as a whole, over half of the fine sediment load is eroded from bluffs (Fig. 17). Below knickpoints, 85% of eroded fine sediment is bluff-derived. Bluff frequency (bluff surface area per square kilometer of land surface) and linear erosion rate increase downstream below knickpoints. The highest channel width-normalized migration rates are found in alluvial channel reaches with high bedload supply, while bedrock slows bluff erosion rates (Fig. 18). Because bluffs are such large sources of suspended sediment, budget accuracy depends on accurately delineating bluff extents. The suspended sediment budgets for each tributary were compared with TSS gaging records from the last decade to assess accuracy. The budget overpredicts sediment loading in the Watonwan, the basin farthest to the west (and thus the driest basin). We are still awaiting sediment fingerprinting data to better constrain upland sediment yields from this basin.



	Le Sueur	Blue Earth	Watonwan	
predicted	208,947	249,060	92,201	Mg/a
observed	224,859	218,612	34,504	Mg/a
pred/obs	0.93	1.14	2.67	

Pie charts show percent of gross sediment supply

Figure 27. GBER suspended sediment budgets. Bluffs are primary sediment sources. About half of the sediment load is sourced below knickpoints [*Bevis*, 2015].

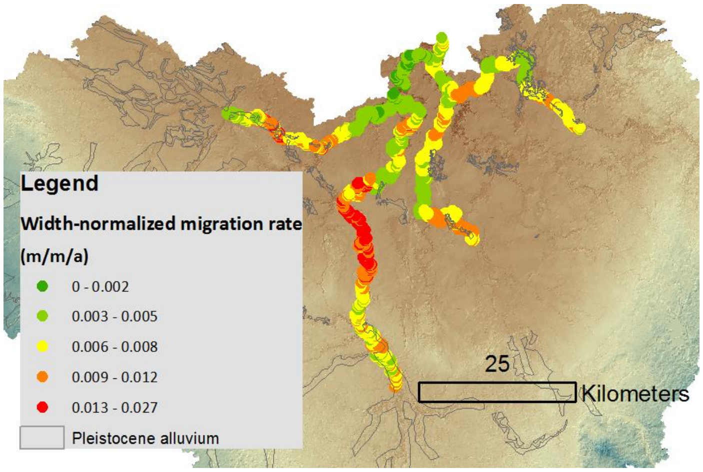


Figure 18. Greater Blue Earth River channel migration rates are highest where sources of bedload are abundant and lowest in bedrock reaches [*Bevis*, 2015].

The completed sediment budget including the spatial location and magnitude of different near-channel sediment sources (bluff, bank, and ravine contributions) are now being combined with a network routing model developed by *Czuba and Foufoula-Georgiou* [2014, 2015].

2. Effectiveness of Wetland Restoration on Reducing Peak Flows and Sediment Loading

Students: Nate Mitchell (M.S. UMD expected July 2015)

Main Collaborators: Se Jong Cho (JHU), Peter Wilcock (USU), Brent Dalzell (UMN), Karthik Kumaraswamy (USU), Patrick Belmont (USU), Ben Hobbs (JHU)

Following on the sediment budget research, we are working with a group of stakeholders to develop a consensus strategy to reduce fine sediment loads in the Greater Blue Earth River basin. Sediment loads, as measured by deposition rates in Lake Pepin, have increased more than an order of magnitude since the early 1800s [*Engstrom et al*., 2009]. Our sediment budget shows that most of this sediment comes from bank and bluff erosion [*Belmont et al*., 2011; *Day et al*., 2013; *Bevis*, 2015]. Along with the increase in sediment load, there has been a commensurate increase in peak flows [*Novotny and Stefan*, 2006; *Schottler et al*., 2014]. This work focuses on assessing the potential impact of wetland restoration on peak flow reduction and the resulting impact on sediment loading from near-channel sources.

For this, we utilized both the Soil and Water Assessment Tool (SWAT), a watershed-scale hydrologic model, and an empirical relationship between discharges in the lower watershed and sediment loading rates developed by colleagues at John Hopkins University (Cho and Wilcock, also part of the REACH project). Results for a wide range of scenarios (e.g., Fig. 19) have shown that hydraulic conductivity is one of the main limiting factors in peak flow and sediment loading rate reductions offered by wetland restoration. High hydraulic conductivities allow for increased seepage in wetlands, reducing peak flow rates in channels more than wetlands with low hydraulic conductivities. The identification of relationships between wetland surface areas and contributing areas as well as between peak flows and wetland extent has allowed us to create a reduced complexity model that can generate results for arbitrary wetland restoration scenarios. With this new model, one can select different wetland placement scenarios, design depths, and hydraulic conductivities, and quickly generate results on both peak flow and sediment load reductions. This new model runs in an Excel file and is intended for use by researchers and regional stakeholders to run scenarios in real-time to help develop a consensus strategy for sediment source reduction in the Greater Blue Earth River basin. The results generated from the simplified model are relatively similar to those obtained directly from SWAT output (Fig. 20).

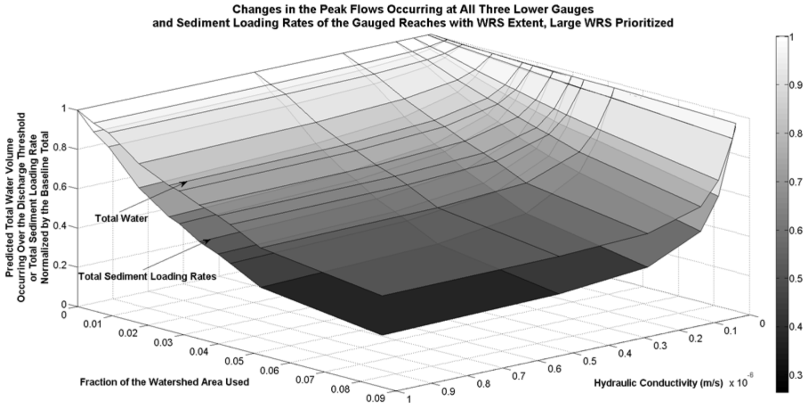


Figure 19. Projected changes in peak flows occurring at the lower gauges and sediment loading rates of the gauged reaches for water retention site (WRS) implementation scenarios prioritizing large wetland sites. Reductions increase non-linearly with the hydraulic conductivity of the sites' bottoms (K) at low K values, but level off as K increases [from *Mitchell et al*., in prep.].

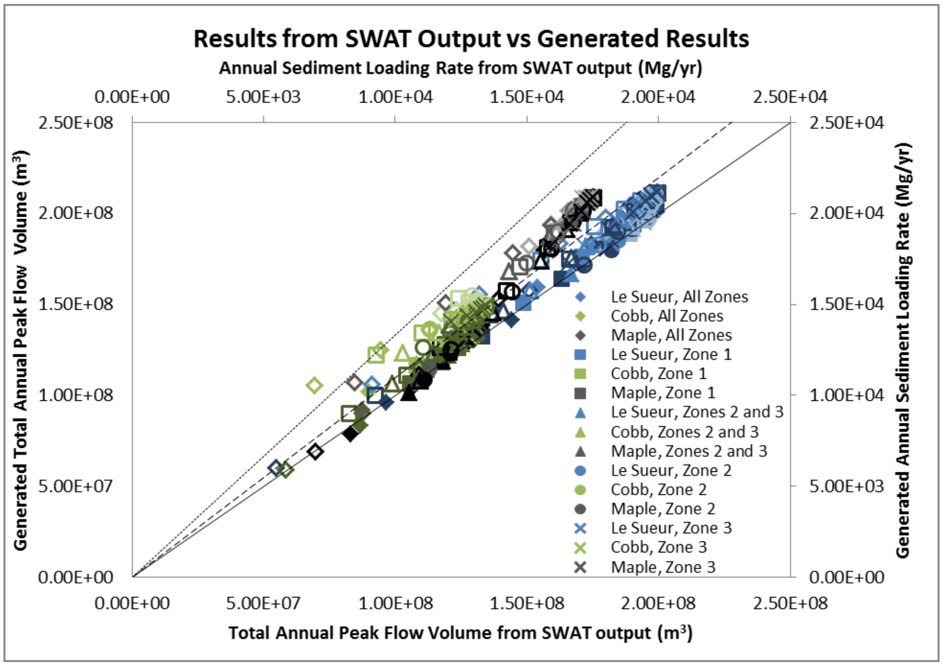


Figure 20. Total volumes of peak flows exceeding the threshold (0.01 $m^3/s/kms^2$) at the three lower gauges and sediment loading rates for the three gauged reaches derived from both SWAT output and generated values. Design depths of 1m, hydraulic conductivity (K) values of 1E-8, 1E-7, and 1E-6 m/s, and all placement zones are used. Symbols for K values of 1E-8 m/s use symbols with lighter shades (blue, green, and grey to black for the Le Sueur, Cobb, and Maple, respectively), symbols for K = 1E-7 m/s use intermediate shades, and symbols for K = 1E-8 m/s use darker shades. The symbols for K = 1E-7 m/s are shown in the legend. Filled symbols designate peak flow volumes, while hollow symbols designate sediment loading rate values. The symbols for zone 3 are an exception to this rule, however, as thick x's represent water volumes for zone 3, while thin x's represent sediment loading rates for zone 3. The solid black line indicates a 1:1 relationship between results from SWAT output and generated results while the dashed and dotted lines represent 1:1.1 and 1:1.33 relationships, respectively [from *Mitchell et al*., in prep.].

3. Holocene-Scale Adjustments to Channel Geometry and Discharge

Students: Courtney Targos (M.S. UMD expected July 2015)

Main Collaborators: Phil Larson (MNSU), Harry Jol (UW-EC)

Given evidence for strong channel adjustments (i.e. widening) over the past hundred years as discharges have increased [*Schottler et al*., 2014], we wanted to assess how channels responded to Holocene-scale changes in discharge. Did channels widen slowly through the Holocene as channel networks expanded, or are there strong variations in channel size due to climatic variations like the mid-Holocene dry period? To assess channel geometry and discharge from the time of deglaciation to the modern, we focused on the Le Sueur River, investigating meander cut-offs preserved on terraces.

Paleochannels, preserved on terraces via meander cutoffs during an incisional period, record the channel geometry and thus discharge throughout a river's history. We measured paleochannel geometry on terraces throughout the Le Sueur River in south-central Minnesota, to track how channel geometry has changed throughout the last 13,400 years. A rapid drop in base level 13,400 yr B.P. triggered knickpoint migration and valley incision that is ongoing today. Since the 1800's, the area has developed rapidly with an increase in agriculture and the amount of tile drainage, directly impacting river discharge by increasing water input to the river. Five paleochannels were identified on terraces along the Le Sueur River from 1m-resolution lidar data. Ground Penetrating Radar (GPR) was used to obtain a subsurface image across paleomeanders to estimate the geometry of paleochannels. By measuring the geometry of paleochannels, we can compare the channel geometry and effective discharge at the time the terrace was being carved to today's conditions. Three lines were run across each paleochannel perpendicular to the historic water flow. Each of the 15 lines were "processed" using the EKKO Project 2 software supplied by Sensors and Software to sharpen the images, making it easier to identify the paleochannel geometry. Paleodischarge was determined using the Law of the Wall and Manning's Equation. OSL samples were collected from overbank deposits to determine the time of channel abandonment. Paleodischarge coupled with depositional ages provide a history of flow conditions on the Le Sueur River.

Results show an increase in channel widths from the time paleochannels were occupied to modern channel dimensions from approximately 20 meters to 35 meters. The change was not constant through time, as all paleochannels analyzed on terraces had similar-sized channels. The best way to estimate paleogeometry was using the 'best interpretation' of GPR data, based on width-to-depth ratios; and paleodischarge was best estimated using Manning's equation with an n value of 0.035. Uncertainty estimates in paleogeometry can change paleodischarge calculations by 150%. Flood frequency analyses suggest a 1.5- and 2-year flood of 76 m3/s and 142 m3/s, respectively, which is comparable to estimations of bankfull based on current channel geometry, validating the methodology. Problems associated with paleogeometry estimations are primarily due to meander bend preservation in the subsurface, challenging GPR interpretation. The increase in channel geometry and discharge implies that the increase in agriculture and tile drainage since the area's development has greatly impacted the Le Sueur River resulting in a change in channel morphometry through increased erosion along the bluffs and banks. This increase in erosion has directly impacted the amount of sediment delivered to the rivers from banks and bluffs, increasing the turbidity in this turbidity-impaired river system.

4. Ecogeomorphic Response to Changing Flows

Students: Laura Triplett (M.S. UMN, 2015)

Virginia Batts (M.S. UMD, expected 2016)

Main Collaborators: Chris Lenhart (UMN)

Results from this study help to better understand and provide evidence for the relationships among vegetation establishment, hydrology, and sediment transport. Understanding these relationships and characteristics within the Minnesota River basin will aid in the development of management actions and the identification of priority management zones necessary to reduce sediment related impairments. Additionally, this work will provide baseline data and methodology for future work related to riparian vegetation, hydrology, and sediment within the Minnesota River basin.

With increasing flows on the mainstem Minnesota River in recent decades, point bars are spending more and more time submerged during the time when major riparian species germinate. This affects vegetation growth and composition on point bars. In comparing vegetation area relative to point bar area across recent years, in general vegetation area was found to increase during lower flow periods and decrease during high flow periods providing evidence for inhibited vegetation growth during high flows. Additionally, higher occurrence of saplings with adventitious growth habits were observed over those without adventitious habits indicating survival of these types of species, mainly willows, during high flow years of 2011 and 2013. In comparing historical flow data with tree core samples taken along the Minnesota River, trees were found to not have established in floodplains prior to high flows observed in the early 1950s and 1960s (or not survived the floods). Additionally, point bar vegetation was found to not be older than thirty or forty years providing evidence for succession from temporary point bar habitats to more permanent floodplain habitats. Lastly, sites in general that were characterized by more dense vegetation were found to have higher average rates of deposition based on a comparison of depth of sediment to root collar with plant age. This last finding is being investigated further via a series of experiments.

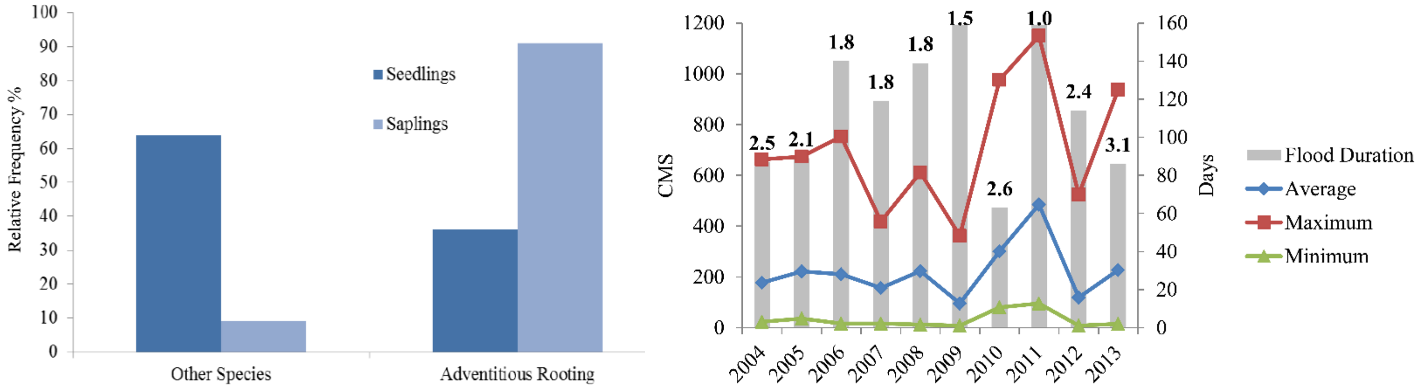


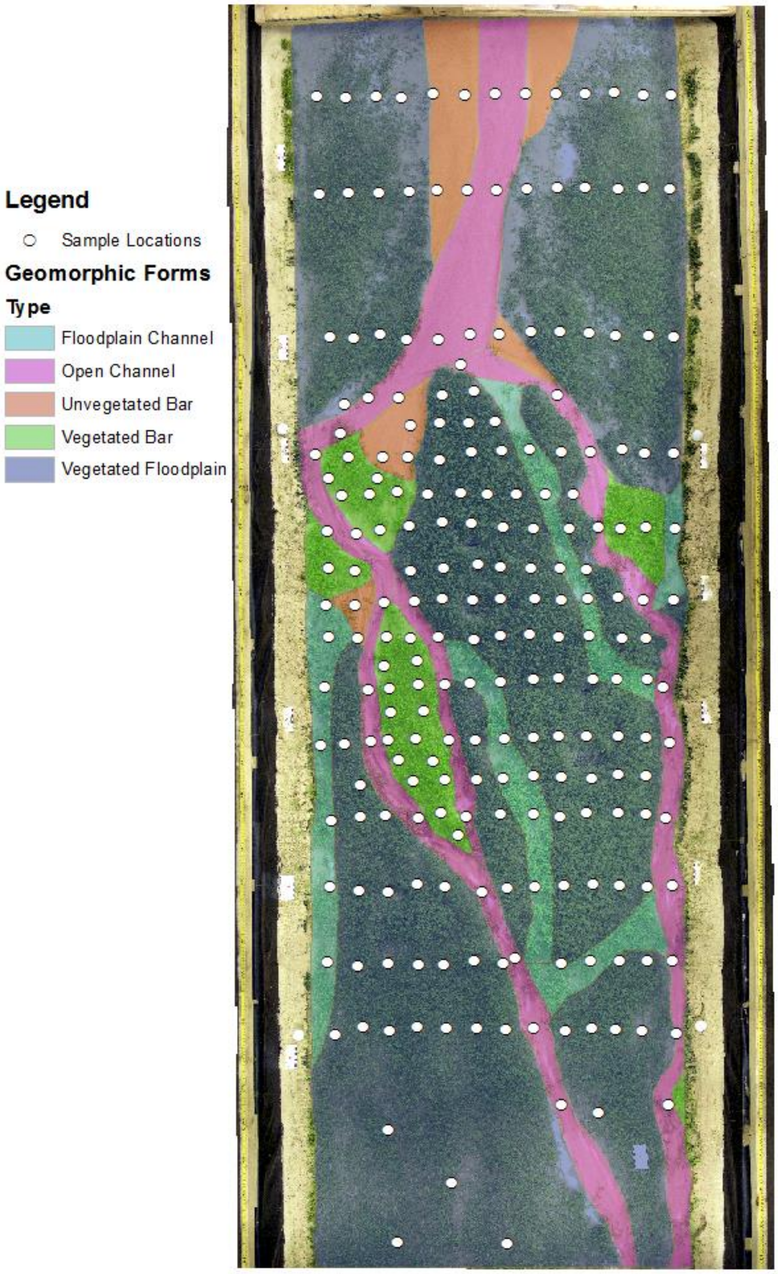
Figure 21. (left) Relative frequency of seedlings and saplings with normal vs. adventitious growth habits within lower Minnesota River basin transect surveys. N=82. (right) Recent flood characteristics in Minnesota River at Mankato, MN, including days of point bar inundation [from *Triplett*, 2015].

A series of flume experiments over the past decade have shown that riparian vegetation is a primary control on river morphology by adding surface cohesion and by trapping and storing suspended sediment. However, due to high spatial and temporal variability in the field, it is difficult to characterize the relationship between vegetation and flood deposition at a high resolution. A better understanding of how fine sediment is distributed through vegetated river corridors is crucial in determining the significance of floodplain storage in an overall sediment budget.

Building on the insights from previous experiments, we are experimentally investigating the role of vegetation density on the quantity and distribution of fine sediment in a self-formed channel network. Our approach is based on the understanding that riparian vegetation influences the spatial distribution of fine sediment deposition by its role in a) the organization of channel networks by the addition of floodplain cohesion, and b) the direct interruption of channel flow.

Our experiments are conducted in a 1.5 x 5 m flume at the University of Minnesota, Duluth. The flume is filled with 0.5 mm, graded to a slope of 1.5%. Water and sediment discharge rates are held constant. Once a braided channel network is established, we halve the water discharge and stop sediment feed to expose channel bars, which are seeded at a specified density. After a growth period of 7 days, discharge and sediment feed are returned and the run is continued. Flow is redistributed into one or two channel threads after two seeding events. We flush this channel network with lightweight plastic sediment in the final hour of the experiment, then remove core samples to characterize the quantity and spatial distribution of the resulting deposit. To date, we have completed one experiment with a high-density seeding. Two additional experiments, one with a low-density seeding and one without vegetation, will be completed by the end of the summer. Results of this study will provide crucial insight into vegetation-sediment feedbacks that contribute to fluvial landform building and channel evolution.

Figure 22. Overbank deposition of fine sediment within a patch of vegetation (alfalfa, Medicago sativa)



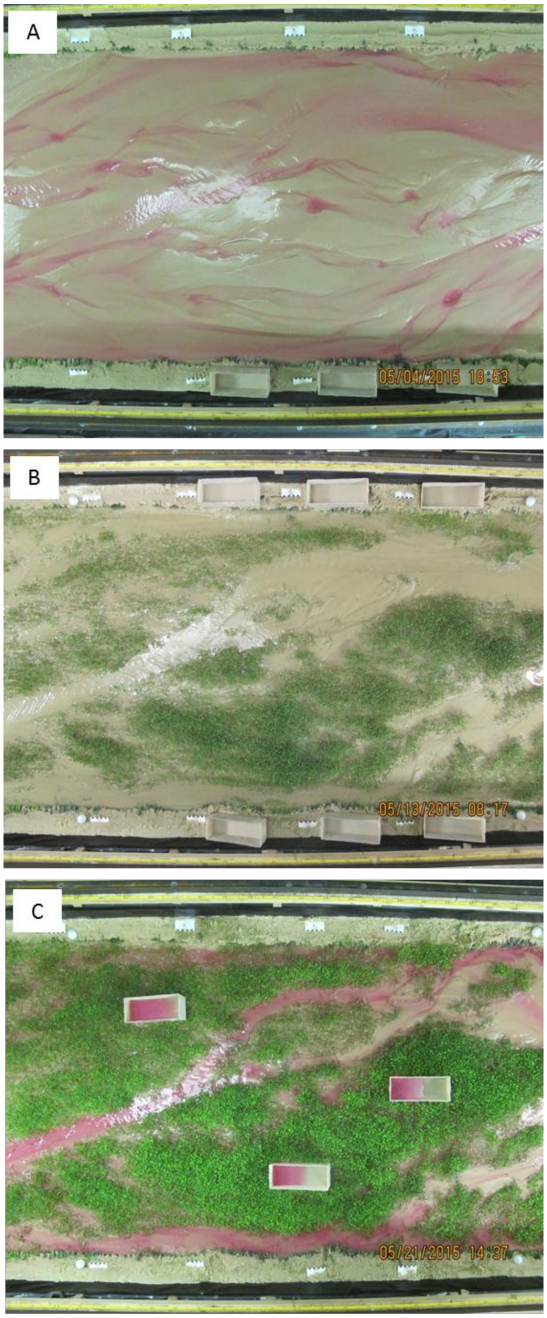


Figure 23. (left) Core samples extracted from the flume following the release of fine sediment.

Figure 24. (right) Reorganization of a braided channel network (A) following two seedings of alfalfa (B,C). Surface cohesion provided by the vegetation constrains channel flow into fewer threads.

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Schottler, S. P., Ulrich, J., Belmont, P., Moore, R., Lauer, J. W., Engstrom, D. R., and Almendinger, J. E. (2014). “Twentieth century agricultural drainage creates more erosive rivers,” Hydrologic Processes, 28(4), pp 1951–1961, doi:10.1002/hyp.9738.

Gillian Roehrig's group:

Graduate Research Assistants: Senenge Andzenge, Engin Karahan,

Devarati Bhattacharya, and Justin McFadden

Overview

Building on the five aspects of collaboration and research earlier identified [*Roehrig et al*., 2014], year three of "The River Run: Professional Development with a Splash of Technology" documented marked progress in each area of (1) Continued teacher collaboration, (2) Curriculum development and classroom implementation, (3) Collaboration and collection of digital artifacts, (4) Socio-scientific issues and technology integration, and (5) Research presentations, articles, proposals.

1. Continued Teacher Collaboration

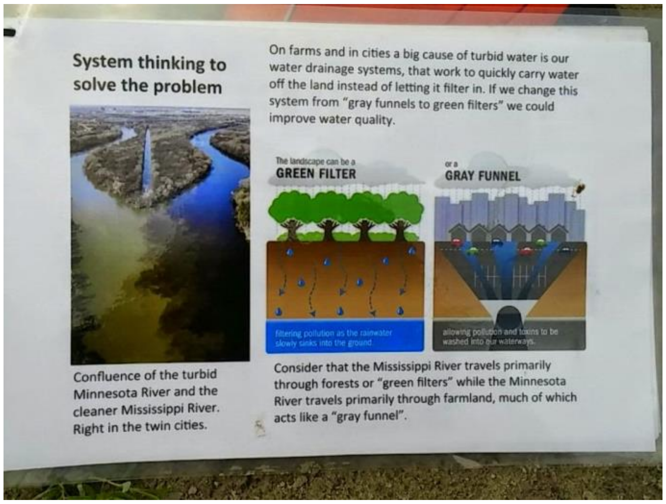
Table 1 in this section outlines and summarizes the collaborative efforts between educational researchers, high school science teachers, and high school students within the context of environmental science education during the 2014-2015 academic year.

Table 1. Educational support and outreach (2014-2015)

Date	Event	Description
Aug. 4th- Aug. 6th, 2104	**Active Learning Experience**	Immersion experience targeted specifically to secondary science teachers. Grounded within place-based and active learning frameworks, workshop topics included instructional strategies and activities for teaching and learning about: formation and ecology of rivers and watersheds, causes and contributors to turbidity, historical, cultural, agricultural development of river civilizations
Aug. 6th- Aug. 7th, 2014	**Curriculum Development**	Development of Content Knowledge specific curriculum geared towards teaching and learning about environmental science within the context of the Minnesota River Basin (MRB) watershed.
Aug. 7th, 2014	**Teacher Enrichment**	Extensive tour the St. Anthony Falls Laboratory (SAFL) research and educational facility. Session emphasis on the availability of SAFL research and facilities to support teaching environmental science relevant to the contexts of MRB secondary science learners

Oct. 2014-June 2015	**On-going coaching and support**	Periodic check-in via face-to-face, email, and telephone
December 2014	**Fall Semester Meeting**	Co-constructed a platform for Spring 2015 Pilot of teaching and learning environmental science grounded within a service learning framework
May 2015	**Spring Semester Meeting**	Reflection on practice: successes, learning opportunities, direction forward using service learning as a framework for teaching and learning environmental science within the context of the Minnesota River Basin.

Active Learning Experience (Aug. 4-6, 2014): This fully immersive active learning intervention was experienced in partnership with Wilderness Inquiry, Ranger Dave Wiggins (National Parks Service), and Secondary School teachers from St. Paul Public Schools. Through formal and informal learning activities, various contexts for teaching and learning environmental science content were explored and shared. Situating discussions of watershed ecology in different historical and cultural contexts invited teachers to practice and expanded on their pedagogical knowledge of environmental science content. Further, the experience offered the teachers inventive ways of connecting foundational science content, emerging learning technologies to address real-world problems within authentic learning environments.



System thinking to solve the problem

On farms and in cities a big cause of turbid water is our water drainage systems, that work to quickly carry water off the land instead of letting it filter in. If we change this system from "gray funnels to green filters" we could improve water quality.

Confluence of the turbid Minnesota River and the cleaner Mississippi River. Right in the twin cities.

Consider that the Mississippi River travels primarily through forests or "green filters" while the Minnesota River travels primarily through farmland, much of which acts like a "gray funnel".

Curriculum Development (Aug. 6-7, 2014): This collaborative experience between the research team and the teachers was a session to share and apply ideas to developing classroom curriculum, both within specific disciplines and interdisciplinary. Teachers drew from their existing and new pedagogical and content knowledge to address teaching objectives and student learning goals in areas of environmental science.

Fall Semester Meeting (December 2014): Using a shared construct of service learning, researchers and teachers co-constructed a platform for teaching and learning environmental science which could focus direct-instruction practices around student-centered constructivist learning experiences. Products from this session would pilot as appropriate in the teacher classrooms during Spring 2015 semester.

Spring Semester Meeting (May 2015): The teachers and research team met face-to-face to share success, learning opportunities, and evaluate the experiences of using service learning as a framework for teaching environmental science within the context of the Minnesota River Basin. The group set an agenda of topics to develop and work into curriculum which could add depth to teaching and learning environmental science.

2. Curriculum Development and Classroom Implementation

A primary focus in curriculum development this year included efforts to address specific types of lessons within teaching and learning environmental science which could be highlighted from its interdisciplinary nature to emphasize particular disciplines as warranted and appropriate. The curriculum incorporates classroom lecture and discussion suggestions, case study libraries, project design activities, short supporting lessons, and larger-scope interactive group research projects.

During spring semester 2015 secondary science student-groups from schools across the Minnesota River Basin engaged in various project-based and service learning experiences, exploring themes in environmental science including watershed ecology, plant and animal biology, river formation, land and watershed management, and human impacts on nature.

Examples of developed curricula can be found on the [project site at this link](http://stem-projects.umn.edu/riverrun/test-page/) (http://stem-projects.umn.edu/riverrun/test-page/)

Project-Based environmental ethics lesson: Teachers and students wrote and received a grant to build a rain garden at the high school. In building the rain garden, student lessons and discussions included: Non Point source pollutants and their impact on Water quality, Sedimentation and its impact on water quality, Tile design and conceptual understanding, Data analysis between tiled and untilled field (water flow).

3. Collaboration and collection of digital artifacts

Technology use focused on supporting pedagogy and developing technological-pedagogical competence with the teachers. Teachers leveraged their expanding knowledge of resources and context for teaching environmental science to access new pedagogies for embracing mobile and other emerging technologies. Student groups from three of four teachers involved in this experience produced end of semester multi-media productions showcasing an important socio-scientific issues relative to their community within the Minnesota River Basin. Student-groups in these cases identified a real world problem relative to their community in the Minnesota River Basin, researched and investigated the issue, consulted with local experts, and shared their findings with their communities.

For ease of access and usability, teachers had individual students and student groups document data collection and other research activities using online blogs.

<u>Environmental ethics land management lesson:</u> (stills from a video project)

4. Socioscientific and Technology Integration Educational Research

This area has represented a significant area of focus in our research on teaching and learning environmental science in the context of the Minnesota River Basin. Addressing socioscientific issues has been one of the main focuses in science education since the Science, Technology, and Society (STS) movement in the 1970s. Despite generally positive attitudes for using controversial socioscientific issues in their science classrooms, only a small percentage of science teachers actually incorporate SSI content into their science curricula on a regular basis. Developing learner’s 21st century skills is fueling many efforts in teacher education. For in-service teachers, professional development opportunities can be a catalyst for reinforcing pedagogical skills with technological knowledge and communicating content in ways that are meaningful and engaging to students. Current science education reforms in the U.S., driven by the Next Generation Science Standards, places heightened emphasis on preparing students for futures in STEM fields. This, therefore, makes it imperative that science teachers integrate technology into their science instruction.

5. Research Presentations, Articles, Proposals

The educational outreach team has, thus far, presented or had the following papers accepted pending presentation at international and regional conferences during 2014-2015:

Karahan, E (2015). Secondary School Teachers' Expereinces of Designing and Teaching Sociocientific Issues-Based Classes and their Students' Understanding of Science and Socioscientific Reasoning. *Doctoral Dissertation, University of Minnesota*.

Karahan, E., Andzenge, S.T., Roehrig, G. (August 2015). Engaging students in community-based issues through authentic problem-based learning experiences. *Paper presentation (accepted) at the annual meeting of the European Science Education Research Association (ESERA), Helsinki, Finland*.

Andzenge, S.T., Karahan, E., Roehrig, G. (July, 2015). Digital Natives, Immigrants, and TPACK: an exploration of secondary science teachers and technology. *Paper presentation (accepted) at the annual MNeLearning Summit, Minenapolis, MN*.

Andzenge, S.T., Karahan, E., Bhattacharya, D., Roehrig, G. (April 2015). Eliciting students' understanding of river geography and socioscientific issues through a critical response protocol. *Paper accepted for presentation at the annual meeting of the National Association of Research in Science Teaching (NARST), Chicago, IL.*

Andzenge, S.T., Karahan, E., Bhattacharya, D., Roehrig, G. (November 2014). Technology integration and water sustainability in STEM education: A professional development experience. *Paper presented at the annual meeting of the Association for Educational Communications and Technology (AECT), Jacksonville, FL.*

McFadden, J. (November 2014).The River Run: Professional development with a splash of technology. *Mississippi River Education Symposium, East Alton, IL.*

Karahan, E., Andzenge, S.T., Bhattacharya, D., Roehrig, G. (November 2014). A technology rich professional development program and its influence on participant teachers' practices. *Paper presented at the annual meeting of the Association for Educational Communications and Technology (AECT), Jacksonville, FL.*

Patrick Belmont

Department of Watershed Sciences

Utah State University

Year 3 Research Results from REACH

NSF Water, Sustainability and Climate project (CBET 1209445)

REACH
Resilience under
Accelerated
Change

This document contains the research summary for the NSF WSC REACH project for year 3 (2014-2015) for PI Patrick Belmont at Utah State University.

Patrick Belmont's students contributing to this project include: Karthik Kumarasamy (post-doctoral researcher), Sara Kelly (PhD candidate), Keelin Schaffrath (PhD candidate), Mitchell Donovan (PhD student), Angus Vaughan (MS student), Shayler Levine (undergrad), Adam Fisher (undergrad), Patrick Adams (undergrad).

Research themes and accomplishments during 2014-2015

The Utah State University-based REACH research group has taken the lead on several initiatives during year 3, including 1) analysis of high resolution topography data, 2) analysis of discharge-suspended sediment relationships for rivers throughout the state of Minnesota, 3) mapping of river channel bathymetry, and 4) watershed hydrology and sediment modeling. Application of the tools and techniques has been concentrated primarily on the Minnesota River Basin, but all are generalizable and portable.

1. Analysis of high resolution topography data

My research group has initiated several studies that expand our capabilities to measure landscape change over relatively short timescales. We have been working at small spatial scales (individual bluffs in the Le Sueur River Basin) to measure erosion with high frequency (daily) using an automated system we designed for structure-from-motion photogrammetry. We have recently completed a study at very large spatial scales (1950 km^2) to measure 'meaningful' change at the landscape scale using two repeat aerial lidar datasets from 2005 and 2012, covering Blue Earth County in south-central Minnesota (including the most active parts of the Le Sueur River Basin). In addition, myself and two of my PhD students were co-authors on a comprehensive review of "Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes", currently in press with Earth Science Reviews.

Passalacqua, P., Belmont, P., Staley, D.M., Simley, J.D., Arrowsmith, J.R., Bode, C.E., Crosby, C., DeLong, S.B., Glenn, N.F., Kelly, S.A., Lague, D., Sangireddy, H., Schaffrath, K.R., Tarboton, D.G., Wasklewicz, T., Wheaton, J.M. (in press) Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. Earth Science Reviews.

1a. Geomorphic change detection over vast areas with spatially variable uncertainty

Repeat surveys of high-resolution topography data enable analysis of geomorphic change and such analyses are becoming increasingly common. However, techniques for developing robust estimates of spatially variable uncertainty have been slow to develop and are underutilized. Further, issues are often encountered in comparing recent to older datasets, due to differences in data quality. Airborne lidar data were collected in 2005 and 2012 in Blue Earth County, Minnesota (1,980 km^2, see Figure 1) and the occurrence of an extreme flood in 2010 produced geomorphic change clearly observed in the field, providing an opportunity to estimate landscape-scale geomorphic change. Initial assessments of the lidar-derived digital elevation models (DEMs) indicated both a vertical bias due to different geoid models and a localized offset strips in the DEM of difference, due to poor co-registration of the flightlines. We tested several approaches to correct for the poor flight line co-registration, including a Fourier transform filter and a spatially variable correction surface that was generated using local, empirical estimates of the offset, the latter of which most effectively corrected for the bias (Figure 2). We then compare different threshold models to quantify uncertainty. Poor quantification of uncertainty can artificially inflate estimates of change and underreport areas of real change. We show the application of a uniform threshold, often called a minimum level of detection, overestimates change in areas where change would not be expected, such as stable hillslopes, and underestimates change in areas where it is expected and has been observed, such as channel banks. Therefore, we developed a spatially-propagated error model applied to the DEM of difference that quantifies uncertainty based on slope, point density, and vegetation in each square meter pixel in the area analyzed (Figure 3). To support the spatially variable error model, we developed a new metric (cloud point density ratio) to quantify uncertainty due to vegetation density by capitalizing on the complete point cloud to describe the density of above-ground features that may prevent the laser from hitting bare earth. It is calculated by taking the ratio of the above-ground point density to the total point cloud point density. Beyond the methodological advances, our results indicate net erosion of 2,625,100 m^3 in the county between 2005 and 2012. Of this, 39% was generated from bluffs, 1% from ravines, and the remainder came from banks and floodplain areas.

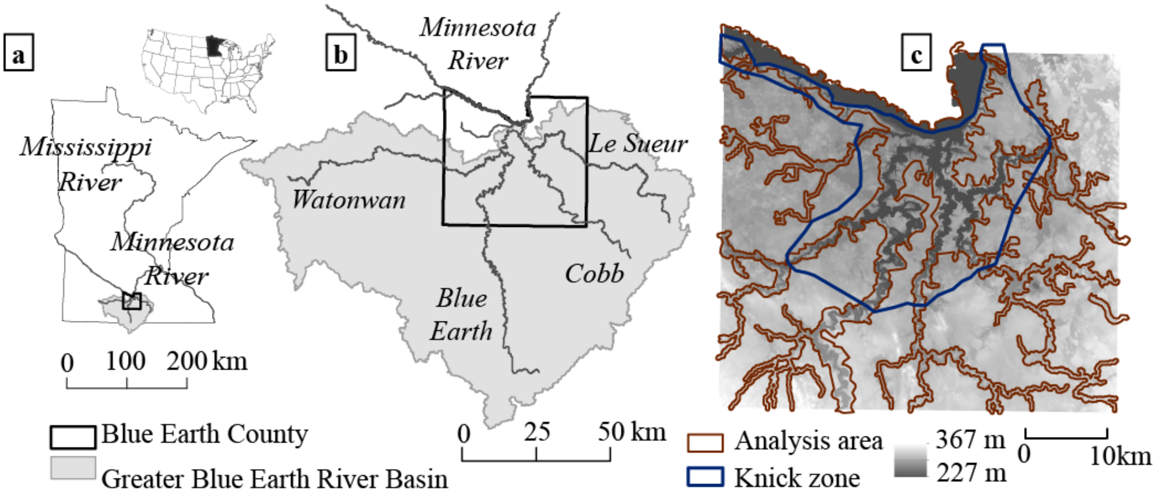


Figure 1. Map of the state of Minnesota showing the Minnesota and Mississippi Rivers and the location of Blue Earth County and the Greater Blue Earth River Basin.

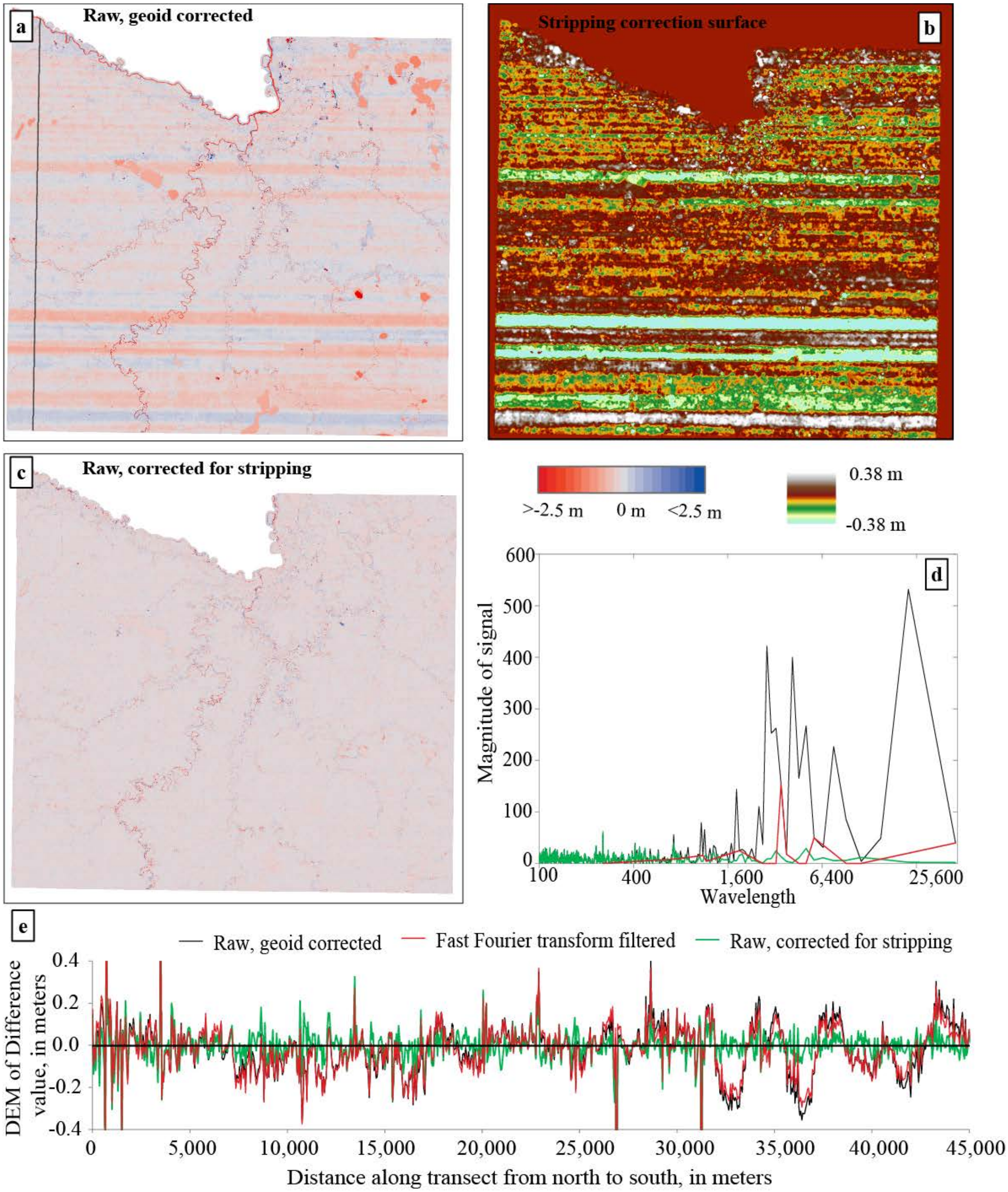


Figure 2. Maps and plots showing the initial characteristics associated with stripping and the correction applied. a) geoid-corrected DEM of Difference showing distinct strips in the east-west direction and the north to south transect, for which we extracted the elevation profile. b) Surface generated to correct the stripping problem. c) DEM of Difference corrected for stripping. Note the east-west strips are no longer evident and the surface is a mix of red (erosion) and blue (deposition). Two plots (d-e) in the figure correspond with data collected at

points on a 50-meter interval on the line shown in the top left panel. d) Power spectra plot where the black line refers to the data from the geoid-corrected DEM of Difference, the red line is the output after a filter based on a fast Fourier transform, and the green line is the output after the application of the stripping correction. e) Elevation profile shows the DEM of difference values for the geoid-corrected (black), fast Fourier transform filtered (red), and final stripping correction (green).

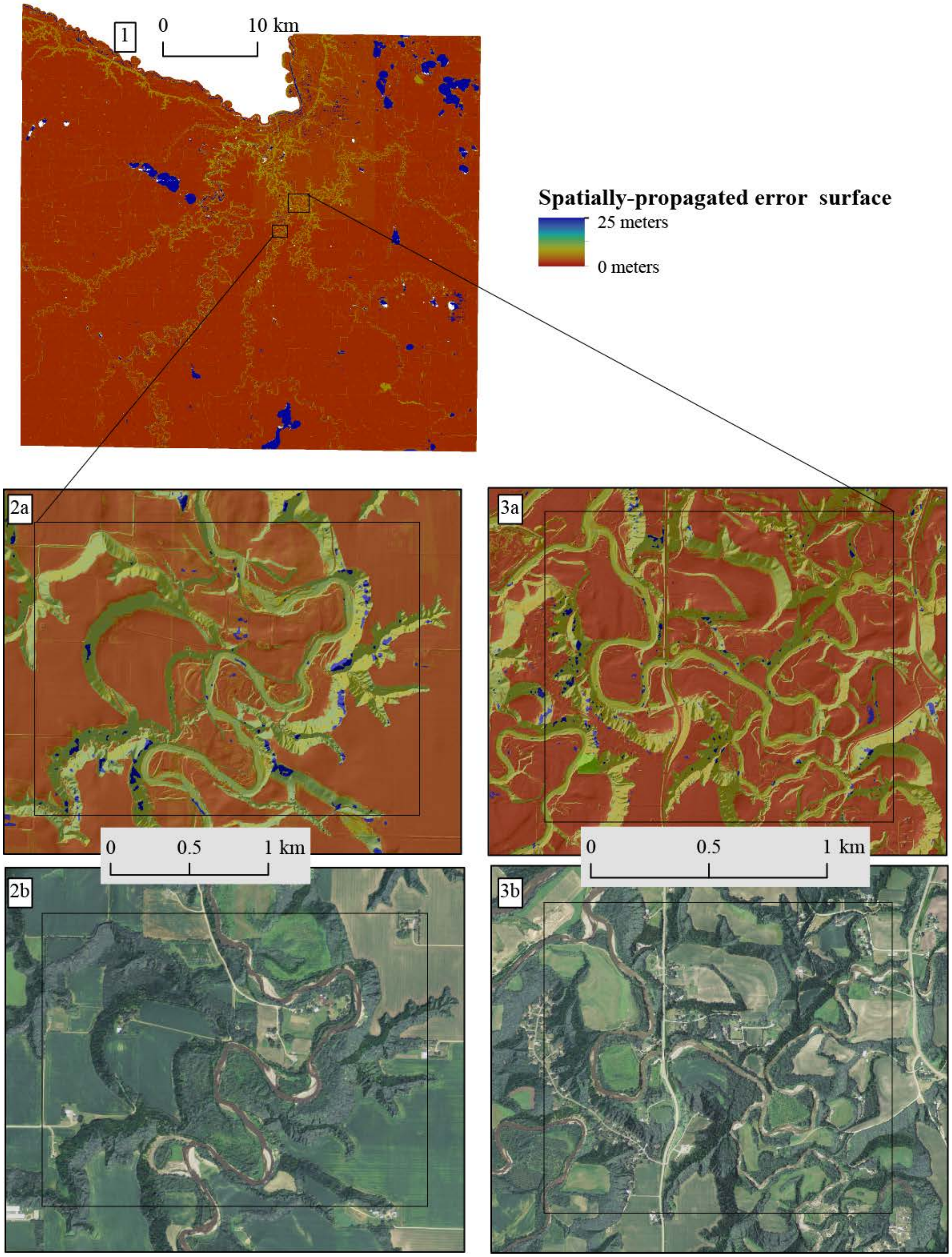


Figure 3. Final surface of spatially-propagated error model for Blue Earth County (panel 1). Equation 1 in the text describes how this surface was calculated. For additional detail, two additional panels are shown at finer scale and underlain by the 2012 hillshade model in areas also used to test the thresholding methods. Panels 2a and 2b show the a) spatially-propagated error model b) and orthophoto for the area used to test different values of minimum level of detection and Panels 3a and 3b are of the area used to test different fuzzy inference systems.

1b. Geomorphic change detection over small spatial scales with high temporal frequency

Excess sediment is problematic in many river systems. The Le Sueur River basin, south central Minnesota, contributes a disproportionate amount of fine sediment to the Minnesota River, which is listed as impaired for sediment under the Clean Water Act, section 303d. High sediment loads can be attributed to the geologic history of the basin over the Holocene as well as agricultural expansion and intensification over the last century and a half. A modern fine sediment budget completed for the Le Sueur River suggests that riverine buffs contribute the greatest proportion of fine sediment to the total sediment load (Day et al. 2013; Belmont et al. 2011), and are likely to be the source all of the coarse bedload material.

Previous research studies of the Le Sueur River have used terrestrial laser scanning(TLS) on an annual to biannual basis to compute volumes of bluff erosion and deposition using geomorphic change detection (Day et al. 2013). This research demonstrated a positive relation between erosion volumes and peak flows between scans. One hypothesis is that high shear stresses at the toe of the bluff lead to toe erosion, over steepening of the bluff, and eventually failure. Another hypothesis is that positive pore water pressures reduce the shear strength of bluff till and lead to mass failures. These hypotheses are not mutually exclusive. We plan to test the importance of both of these hypotheses using field observations and physically-based modeling. We will build and validate a hydraulic and bluff erosion model at two actively eroding bluffs on the Le Sueur River (Figure 4). We have collected bathymetry, velocity, discharge, water surface elevation and grain size distribution data at each of the bluff sites. We established a Structure from Motion (SfM) photogrammetry platform in April 2013 to take daily photographs of the bluffs for calculations of geomorphic change. Photos from the first 16 months of observation have indicated a total of 18 significant erosion events (Figure 5). Ongoing work is quantifying the total amount of sediment eroded during each of these events, which will be used to develop a process-based model of bluff erosion. In May 2015 we installed 20 additional trail cameras that will take daily photographs of bluffs distributed throughout the Le Sueur, Blue Earth and Watonwan rivers.

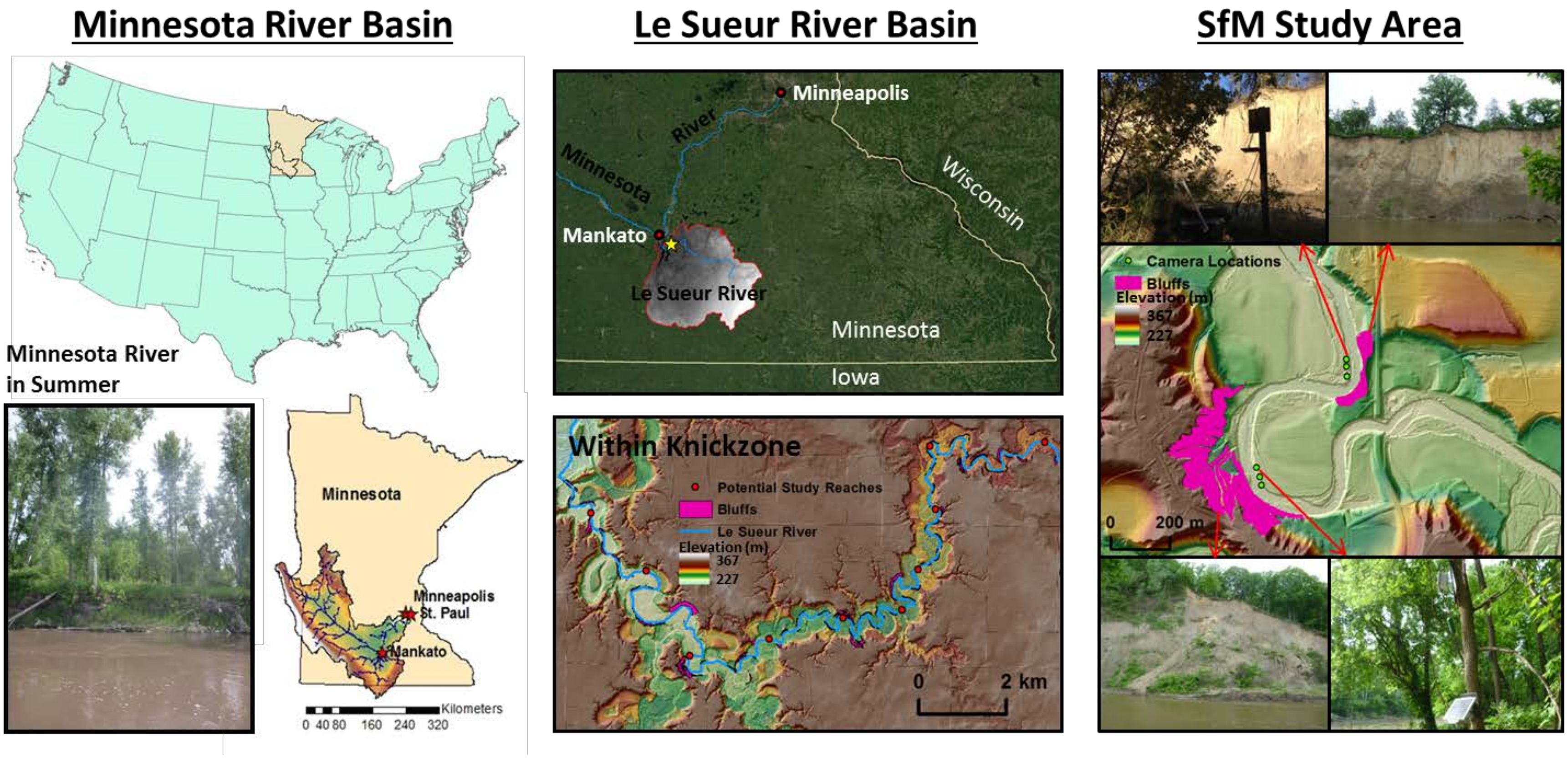


Figure 4. Left: Overview map of the Minnesota River basin with photo of the Minnesota River in summer. Center: Location of the Le Sueur River basin (watershed boundary in red) and close up DEM within the knickzone highlighting bluff locations in pink. Right: Locations of the Structure from Motion remote sensing platform with photos of the overly consolidated bluff above and the normally consolidated slump below.

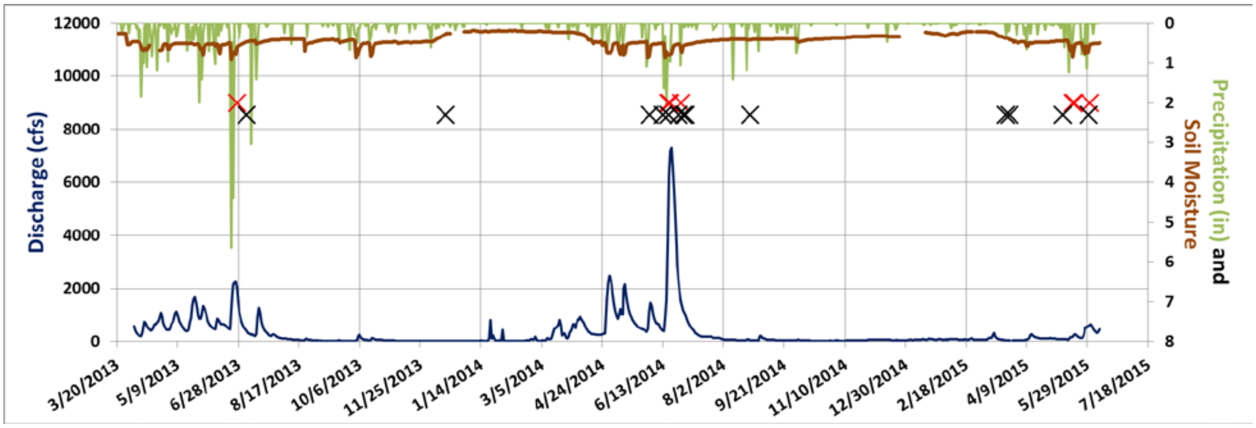


Figure 5. Results from 15 months of Structure from Motion monitoring of two bluffs in the Le Sueur watershed, southern Minnesota. Instances of bluff erosion (indicated by black Xs for the upstream, normally-consolidated bluff and red Xs for the downstream, over-consolidated bluff) are indicated with respect to discharge (blue line), precipitation (green bars) and soil moisture (orange line). Ongoing work is modeling the various erosional processes that occur under different conditions.

2. Analysis of discharge-suspended sediment relationships for rivers throughout the state of Minnesota

Minnesota regulates suspended sediment loads by grouping watersheds into four nutrient regions: rivers in the northern, central, and southern regions and the Red River of the North mainstem each have separate suspended sediment standards (Figure 6). Total Suspended Solids (TSS) concentrations are required to not exceed 15, 30, 65 or 100 mg/L, respectively, more than 10 percent of the time over a multiyear window. The regional criteria are based on two lines of evidence: 1) statistical analyses of paired biological and water quality (i.e. TSS) data to determine ecologically damaging threshold TSS concentrations and 2) analysis of TSS data from “least impacted” and reference streams (Minnesota Pollution Control Agency, 2011). The different standards are, to some extent, a recognition of the different suspended sediment regimes in different parts of the state, produced by diverse geologic, geomorphic, climatic and land use settings and histories. However, the boundaries are based on the regions used to regulate nutrients, for which transport and delivery processes do not entirely overlap with those for sediment. A likely result of that mismatch is that the TSS standards for some rivers may not be consistent with the geomorphic settings and processes that control sediment delivery to the river network. This research is aiming to achieve a more detailed understanding of the factors controlling sediment regimes across the state. There is good reason to believe sediment supply and transport regimes vary systematically across the state, based on unique geologic, climatic, hydrologic, geomorphic and land use settings and histories.

Suspended sediment is often a non-capacity load; transport rates are dependent not only on the transport capacity of the river, but also on the availability of fine sediment. Therefore, stream power-driven transport models such as those used for bed load prediction are not suitable, and empirical relations are used instead. Sediment rating curves describe the average relation between river discharge (Q) and SSC at the location where the data were measured; the curves are typically derived from statistical regression on the Q and SSC data. The curves most commonly take the form of a power function:

$$SSC = aQ^b \qquad (1)$$

where *a* and *b* are the sediment rating coefficient and exponent (Asselman, 2000; Fan et al., 2012; Hu et al., 2011; Mimikou, 1982; Sadeghi et al., 2008; Syvitski et al., 2000; Warrick, 2014; Yang et al., 2007). Power function curves imply continually increasing SSC with increasing Q; they incorporate the influence of amplified stream power at greater discharge as well as the degree to which new sediment sources are accessed during conditions that cause high discharge (Figure 7). Figure 8 maps the magnitude of the exponent (b) in Equation 1 for all gages that have 10 or more years of data since the year 2000. The spatial patterns indicate steep power function relationships in the lower reaches of Minnesota River tributaries (in the knick zone reaches responding to base level fall, as documented by Belmont, 2011 as well as in southeastern Minnesota, where steep bedrock channels debouch into wide, low gradient alluvial valleys. With the conceptual understanding that channel dynamics (meander migration, fluvial undercutting of bluffs, channel widening, etc.) are likely controlling these Q/TSS relations, we are working to extract near-channel morphometrics to explain these spatial patterns.

Understanding the controls on Q/TSS relationships remains an intriguing topic from a basic science perspective, especially with the availability of high resolution topography data and increasing computational power that can take advantage of the immense amount of information contained therein. Understanding differences among Q/TSS relationships also has important implications for land and water management, insofar as they are indicators of sensitivity and vulnerability of systems to erosion. We seek to understand spatial and temporal patterns in those relationships by asking the following questions:

1.) Which landscape or channel characteristics most influence the shape of Q/TSS relationships? Why are some river systems more sensitive to increases in discharge than others? Do Q/TSS relationships vary seasonally?

2.) How can a better predictive understanding of Q/TSS relations be used to improve existing water quality regulations, water and land management, and restoration practices?

3.) Have TSS concentrations changed over time? How do non-stationary hydrologic conditions affect Q/TSS relationships? To what extent can Q/TSS rating relations be used to forecast TSS concentrations under altered hydrologic regimes?

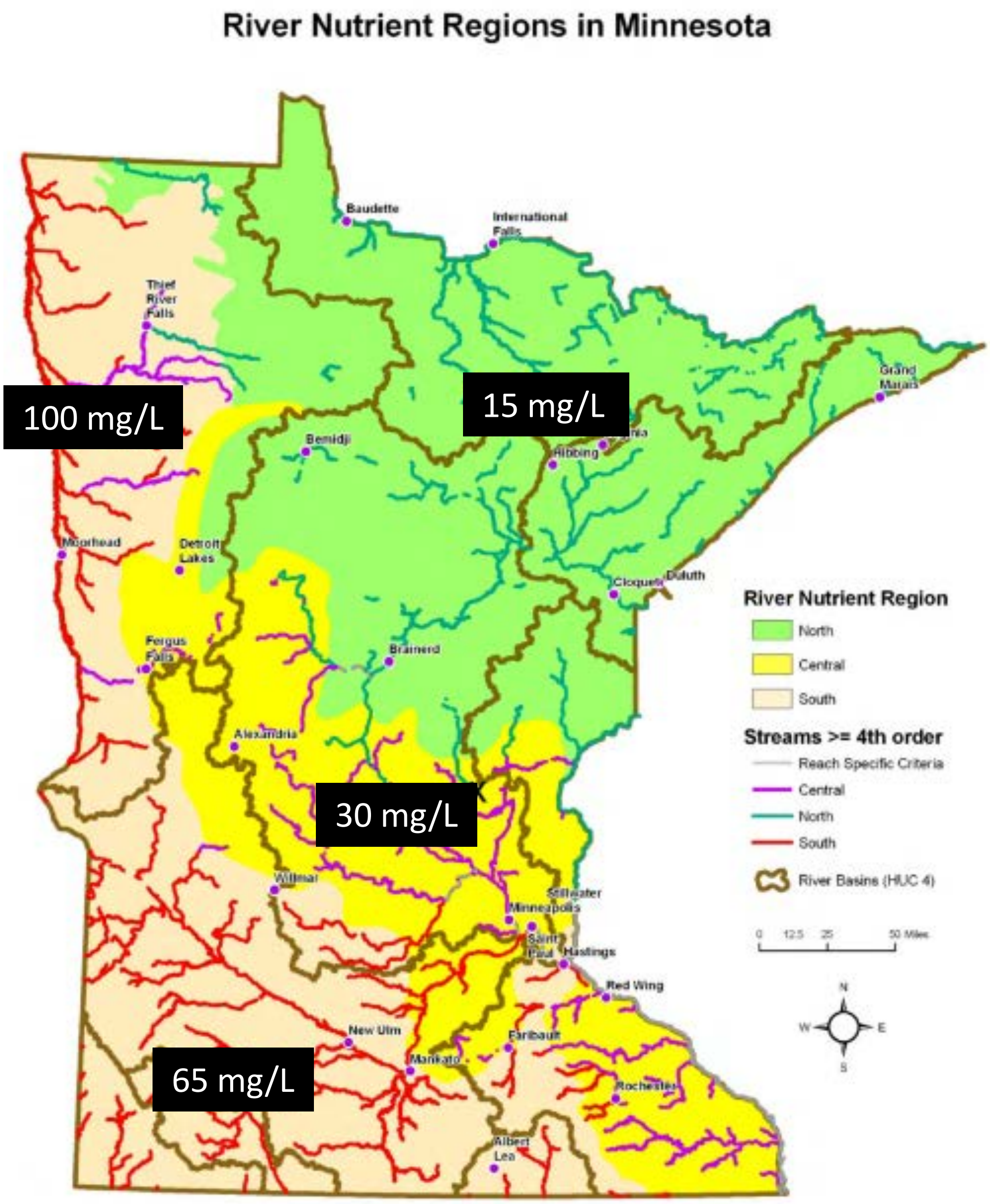


Figure 6. River Nutrient Regions for Minnesota, with TSS concentration thresholds shown. From Minnesota Pollution Control Agency (2011).

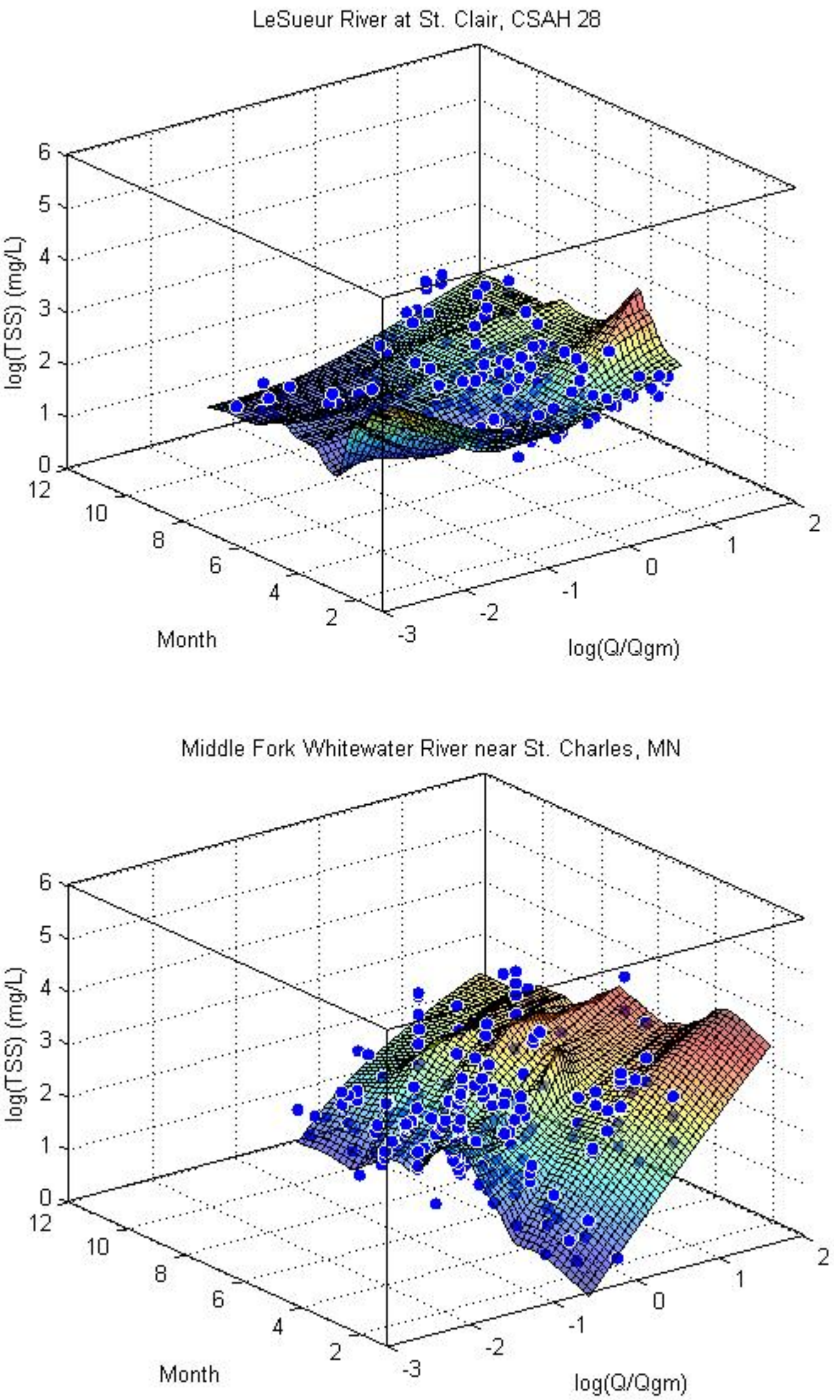


Figure 7. Examples of Q/TSS relationships with fitted LOWESS surfaces, showing seasonal variation in the Q/TSS relationship. Data are from (top) the Le Sueur River at St. Clair, MN and (bottom) The Middle Fork of the Whitewater River near St. Charles, MN.

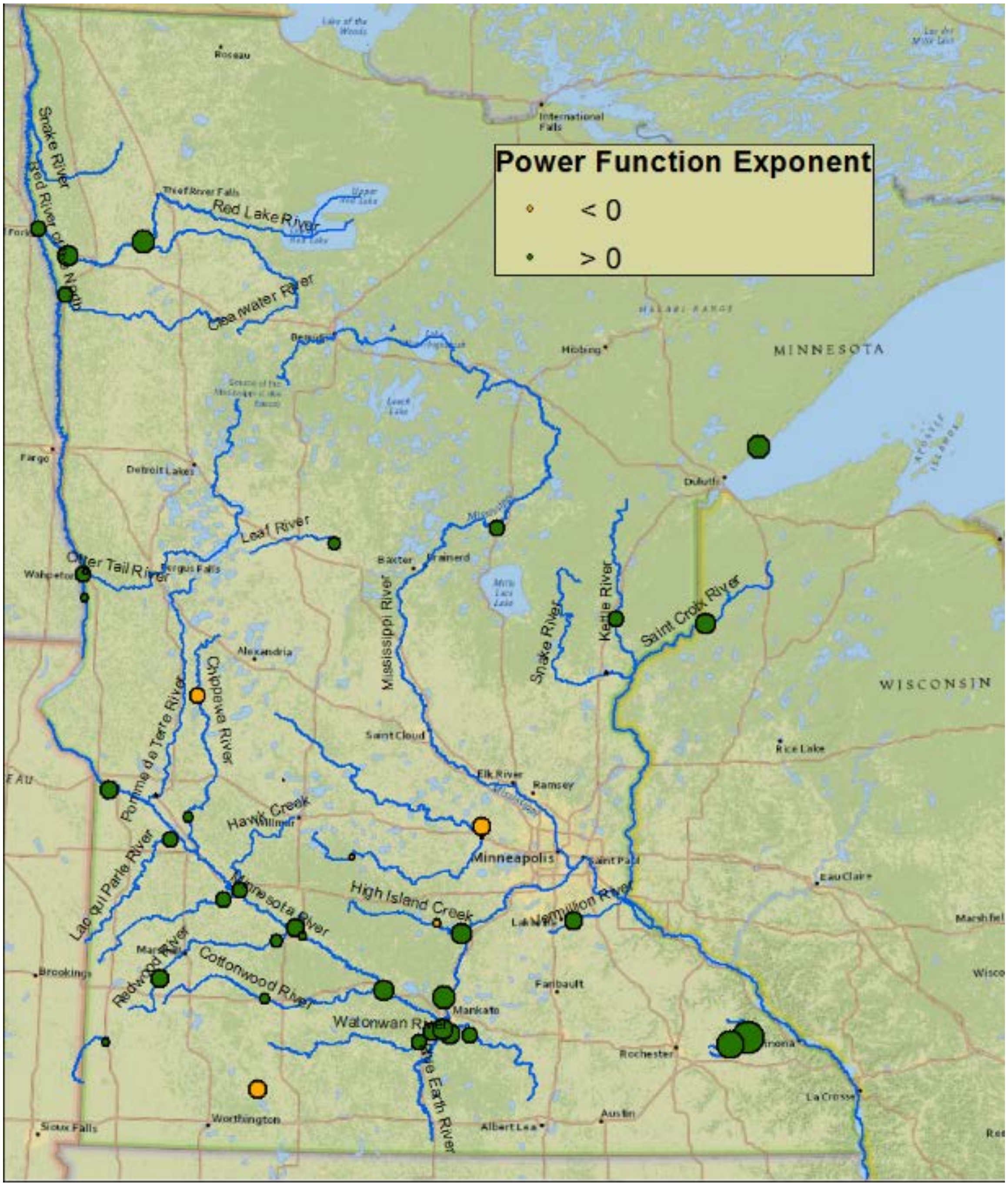


Figure 8. Power function exponent values for study gages. Dots representing gages are sized according to the value of the exponent. Negative exponents are shown in orange, positive exponents in green. Note the large exponents in MRB tributary gages near the confluence with the Minnesota River (i.e. within the knickzone) as well as in the southeastern part of the state and in some of the Red River of the North tributaries. Small or negative values occur in MRB tributary gages above the knickzone and in Upper Mississippi tributaries.

3. Mapping channel bathymetry

High resolution topography data from aerial lidar is dramatically enhancing our abilities to identify critical features and measure geomorphic change over vast areas. However, most lidar datasets do not contain topography data within the channel itself because the wavelengths utilized are fully attenuated even in shallow water. This is especially concerning because river channel networks tend to be the most dynamic 1% of the landscape. Because REACH is strongly focused on understanding in-channel dynamics, obtaining accurate maps of channel bathymetry over large areas is critical.

Beginning in summer 2013 and continuing in summer 2015 we are mapping extensive areas of the Minnesota River and Le Sueur River channel beds using an Acoustic Doppler Current Profiler coupled with a real-time-kinematic GPS system. We have developed a system that allows our rtkGPS to tie into the Minnesota Department of Transportation Continuously Operating Reference Station Network, using a CDMA-enabled cell phone. This allows us to get real-time corrections for GPS locations with precision of 2-3 cm. All of this instrumentation is loaded on a 17’ cataraft with an outboard motor and data is assimilated on a laptop or tablet computer (Figure 9, top panel). As of summer 2015, we have mapped a total of 110 km of the mainstem Minnesota River. The resulting datasets will be used for modeling of hydrology, morphodynamics, light penetration, mussel habitat, and nutrient assimilation.

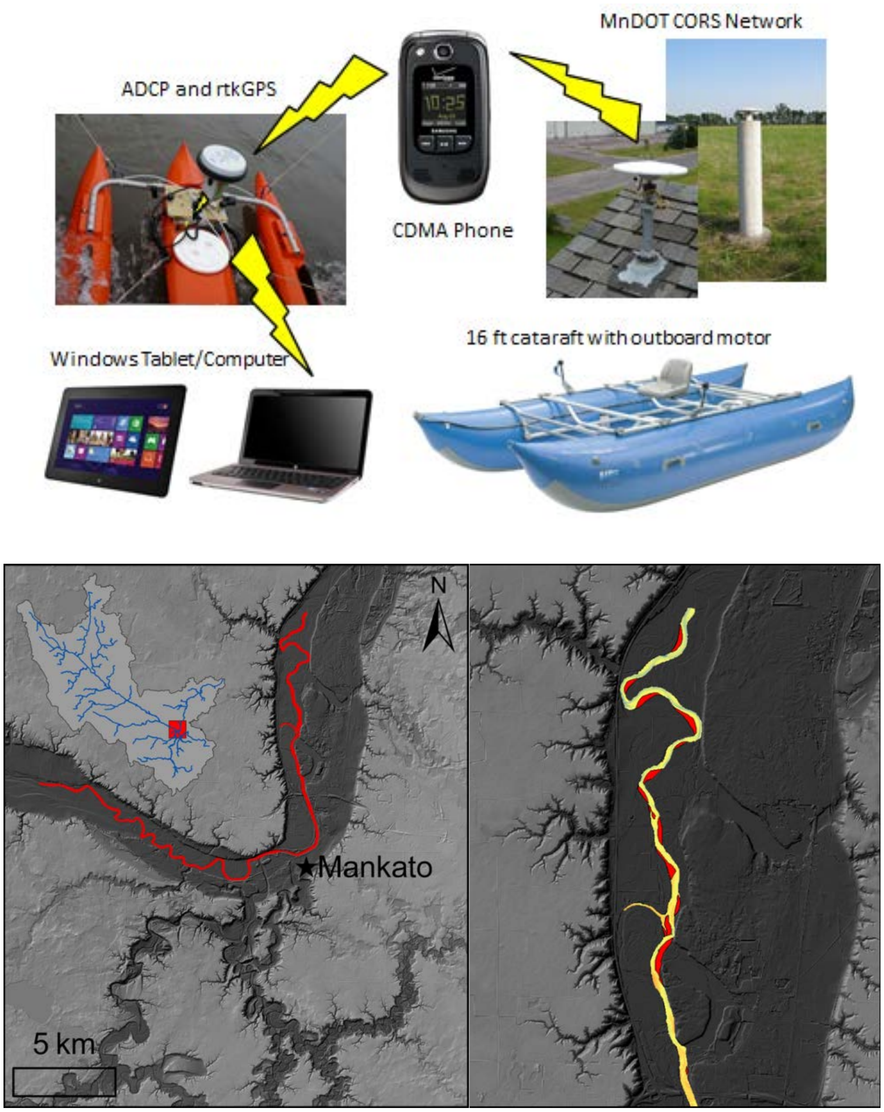


Figure 9. Top Panel: illustrates our system for rapid channel bathymetry mapping. Bottom Panel: show the 33 km reach of the mainstem Minnesota River that we were able to map in six days during summer 2013.

My research group will be utilizing this bathymetric dataset along with morphodynamic modeling to explain how local sediment supply, bank cohesion, and bar morphology interact with bed topography and hydraulics to control meander migration rates and morphodynamics in the Le Sueur and Minnesota Rivers, south central Minnesota. In a complementary pilot study, we will be exploring the same phenomena in the Fall River, Rocky Mountain National Park, Colorado. These meandering rivers provide unique opportunities to identify and model how local sediment supply, bank cohesion, and bar morphology interact with bed topography and hydraulics to control meander migration rates and morphodynamic evolution in strikingly different alluvial valley settings, with differences in slope, valley confinement, and lithology. Specifically, we hypothesize that reaches with local, coarse sediment supplies will exhibit faster rates of morphodynamic change and meander migration than reaches without such supply, all else constant.

There are important feedbacks between coarse sediment, channel topography, and meander migration. Bedload sediment transport is necessary for the creation of channel bedforms. Large bedforms or macroforms, such as bars, topographically steer flow toward the opposite bank, which promotes meander migration (Church and Rice 2009; Ikeda et al. 1981; Dietrich and Smith 1983). Conversely, an imposed meandering planform encourages bar deposition and meander migration (Harrison et al. 2011). Accordingly, we hypothesize that meandering rivers that have access to a local bedload supply at the channel margins will construct bedforms, migrate faster, and thus recruit more material from the channel margins. We expect to capture this positive feedback in natural river reaches and morphodynamic models.

4. Watershed hydrology and sediment modeling

REACH is developing innovative and robust ways to model rainfall-runoff and implications for erosion, transport and deposition of sediment as well as transport and assimilation of nutrients. We have chosen to develop a set of nested Soil and Water Assessment Tool (SWAT) models for the entire Minnesota River Basin, Greater Blue Earth River Basin, and Le Sueur River Basin. SWAT is commonly applied for watershed-scale planning and management and has an enormous user base of researchers, federal, state and local agency staff, and industry professionals. The model is quite useful for making some predictions (e.g., rainfall-runoff simulation), but has critical problems in other areas (e.g., it does not simulate channel dynamics in any process-oriented manner). Thus, we plan to use the robust components of the model to provide inputs to more sophisticated models and plan to provide new solutions to improve components that are currently inadequate. In addition, this model serves as an efficient interface between our economic and biophysical models.

Changes in hydrology resulting from tile drainage and land use change have been implicated as the primary drivers of failing water quality objectives relating to higher turbidity in the Le Sueur River basin (Schottler et al. 2014). We have calibrated and validated a high resolution SWAT model to determine the ability of the model to reproduce hydrologic effects of agricultural drainage (Figure 10). In parallel, we have developed a reduced complexity hydrologic model with an empirical sediment production function to predict changes in sediment loading associated with increased or decreased future flow regimes. Remediation approaches, such as wetlands and land retirement have been proposed as solutions to reduce turbidity with the use of models such as SWAT (Gassman et al. 2007).

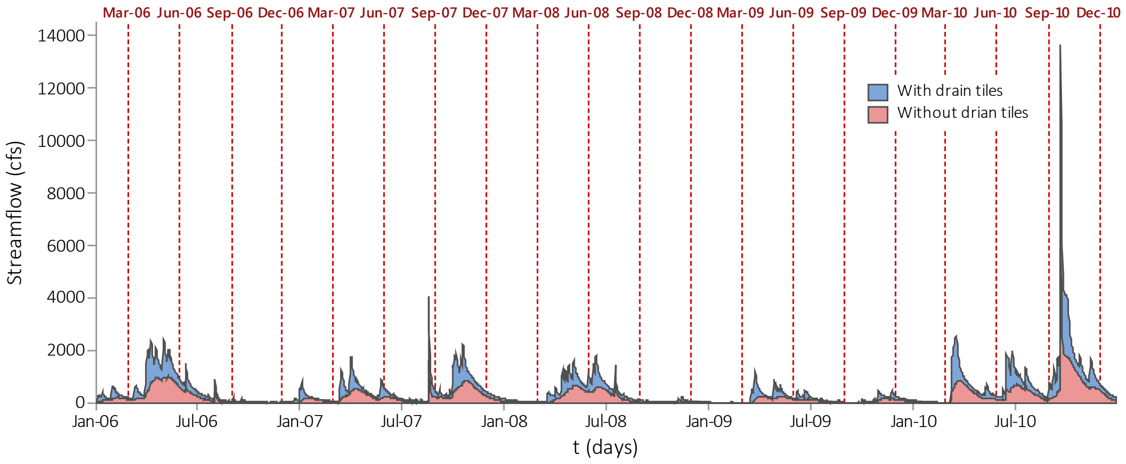


Figure 10. Stream flow outcomes predicted from SWAT considering no drain tiles and drain tiles for agricultural land with less than 2.5% slope.

We are also utilizing SWAT to demonstrate how multiple parameter combinations can result in similar outcomes, meaning completely different characterizations of a physical system can produce the same outcomes leading to variability in management and policy decisions (i.e., problem of model equifinality). Figure 11 shows the Nash Sutcliffe model evaluation criterion for 1200 SWAT model runs of the 2880 km^2 Le Sueur River Basin, with a simplified representation of land use to decrease computational demands. Results indicate that there are many parameter combinations that result in acceptable (> 0.5) to very good (>0.7) model calibration.

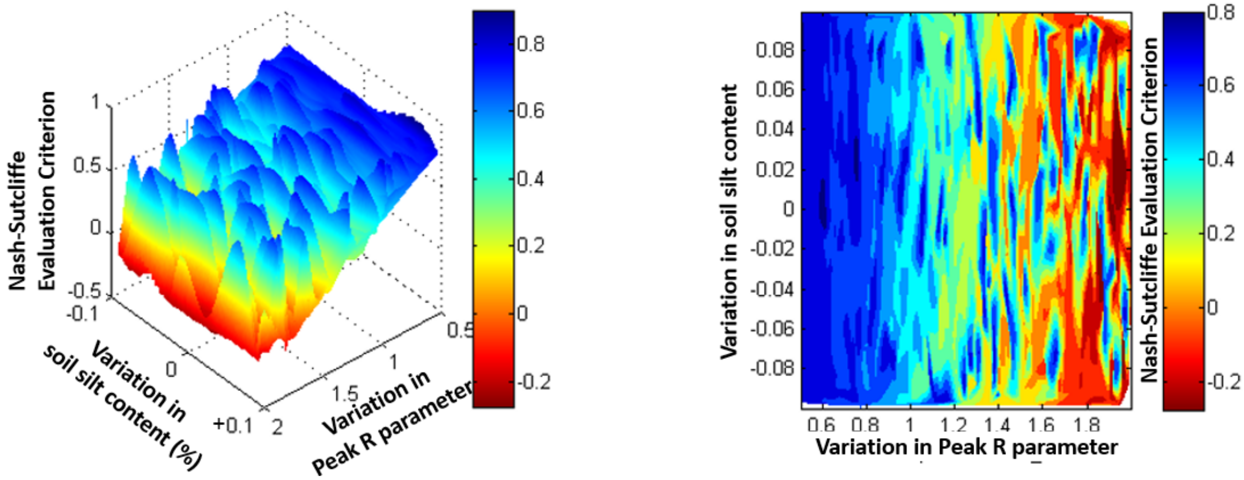


Figure 11. Nash Sutcliffe evaluation criteria resulting from 1200 model runs of SWAT for the 2800 km^2 Le Sueur River Basin. Six different hydrologic parameters, including silt content and Peak R parameter, were varied across reasonable ranges.

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Research Topics and Progress during 2014 - 2015

Economics group: Catherine Kling, Sergey Rabotyagov (faculty); Yongjie Ji (postdoctoral research associate); UW graduate students Zhengxin Lang and Nahyeon Bak

Brief summary of work

- **Land Use Modeling and Applications**

We extended last year's work on dynamic crop choice models with Iowa data into the four main areas in the Upper-Mississippi River Basin (which includes the Minnesota River Basin). In the crop choice framework, we consider forward-looking farmers who take crop system dynamics into consideration (rotational effects of corn-soybean crop system). The model is estimated econometrically using fine-resolution spatial data. The dynamic crop choice model is being used in two applications: water quality implications of land use change (crop choice) in different climate change scenarios and prediction of cover crops based on observational crop choice data. Currently, the water quality implication associating with land use change is analyzed based on the Environmental Policy Integrated Climate (EPIC) models. Integrating land use (crop choice) models with well calibrated SWAT model for Minnesota River Basin will be the next steps.

  - Dynamic Land Use Modeling and Water Quality Implications

Facing changing market incentives, farmers adjust their land use decisions (crop choice) accordingly to maximize profit. Since there are agronomic benefits from growing corn and soybeans in rotation, the crop choice decision is naturally dynamic; that is, when farmers decide to grow corn or soybeans they should rationally incorporate the impact of these decision on the profitability of future rotations. Several existing papers have linked land use decision models with water quality models to analyze the effects of land use change on water quality. However, these papers have employed simple, static models of land use change. In this work, we link an explicitly dynamic econometric model of crop choices with the Environmental Policy Integrated Climate (EPIC) model to analyze water quality implications in different scenarios. This work has two stages. The first stage is the estimation of dynamic discrete choice land use model, similar to DePinto and Nelson (2009), but using the estimation strategy proposed in Arcidiacono and Miller (2011). This land use model generates field-level spatial crop choice probabilities reflecting farmers' forward-looking behavior which are aggregated and incorporated into EPIC in the second stage. Two important policy scenarios have been analyzed. In the first scenario, the changes in land use and the consequences for downstream water quality associated with a permanent increase in corn prices relative to soybean prices were assessed. In the second set of scenarios, we examined the effects of climate change on water quality via land use (crop choice) change by using a set of regionally down- scaled future climate scenarios selected from a set of recent meteorological climate models. Briefly, the dynamic land use model capturing both forward-looking behavior and rotational effects have a better performance than the static model in modeling observed cropping patterns, and, for different policy scenarios, different modeling methods do give difference prediction in crop sequences. However, this difference manifests itself in minor modeled changes in nitrogen and phosphorus losses based on EPIC simulations.

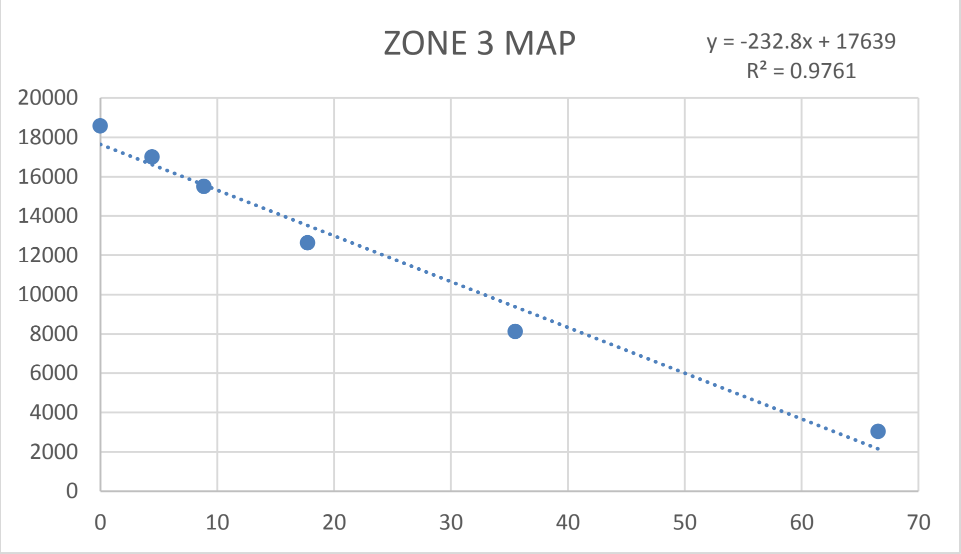
- Estimating Adoption of Cover Crops Using Preferences Revealed by a Dynamic Crop Choice Model

In this study, using a structural dynamic crop choice model, we build a framework to predict the adoption of cover crops and evaluate the subsequent water quality benefits in a number of future scenarios. Our proposed framework combines (1) a dynamic crop choice model, and (2) the use of relative change in revenues to reflect uncertainties associated with adoption of cover crops. With the spatially detailed land use data and other economic data from various sources, we have estimated a dynamic discrete choice crop choice model. The estimated coefficients are generally well expected and relative preferences for crop net revenues are in line with previous research. Based on the estimated parameters, we also extend the model framework to predict the choice probabilities of cover crops under a variety of scenarios. The primary results show relatively high predictions of probabilities to adopt cover crops under all scenarios. Although our results match quite closely the cover crop adoption rates presented in a recent survey (CTIC-SARE, 2014), they appear rather inflated when compared to USDA's official Census of Agriculture state-wide estimates. Given that we place more confidence in the USDA Census estimates, we propose a calibration remedy based on readjusting the alternative specific constants associated with cover crop options to calibrate the model so that the base scenario probabilities match the observed share of cropland with cover crops in the NASS Census of Agriculture 2012 data. Using such aggregated data for field-level model calibration appears necessary prior to using results for policy analysis.

- **Spatial optimization of wetlands restoration: A case of Le Sueur Watershed in Minnesota River Basin**

  The Minnesota River Basin (MNRB) currently provides over 90% of Lake Pepin's sediment load, which adversely affects water quality, agricultural output and the ecological integrity of stream ecosystems. The function of wetland systems for the filtering and the treatment of sediments has been recognized by environmental engineers that specialize in the area of water purification. Constructed wetlands can reduce the peak flows of the rivers and then decrease the sediment loading rates according to the prediction results of Soil and Water Assessment Tool (SWAT). An ongoing study (Mitchell et al. 2014) shows that with 50% of total Water Retention Sites (WRS) area used in the Le Sueur Watershed, a sub-watershed of the MNRB in South-Central Minnesota, the predicted peak flow can be reduced by about 40%; while with 85% of WRS area used, the peak flow will be reduced by around 70%, and the sediment loading rate can be decreased by more than 75%. The goal of this work is to formulate a spatial optimization model for wetlands restoration to maximize sediment reduction in the Le Sueur Watershed, while also minimizing the total costs. The ongoing research by University of Minnesota will provide this project with spatial information and SWAT data with respect to peak flow and sediment reduction by wetlands. The area and location information of each WRS is available now. For the cost data, we use the data from Minnesota Farm Real Estate Sales as the opportunity cost for wetlands restoration. Both engineering cost and fixed cost will be estimated according to a wetlands restoration report from USDA (http://www.ers.usda.gov/media/1784721/err183.pdf). We start with a simple optimization problem (maximizing sediment reduction subject to a budget constraint) and build complexity into the decision by incorporating additional spatial constraints. Simple optimization results are being generated currently and the more complex spatial optimization program is being formulated using integer programming techniques.

Figure 1. A sample relationship developed between extent of artificial wetlands and mean annual sediment load in the Maple River of the LeSueur Watershed (underlying data provided by Nathaniel Mitchell). The coefficient on the linear trend represents marginal estimated annual sediment load reduction (in metric tons) due to a 1 km^2 increase in artificial wetland area and is used as a proxy for the sediment reduction benefit in spatial optimization.



- **Assessing farmer’s crop choice and adoption of conservation technologies using a real options approach**

Recently, new agricultural conservation technologies including artificial wetlands, modified tile drainage and in-channel technologies (e.g., bluff stabilization) for improving water quality in agriculture-dominated watersheds have been introduced but these new practices have been slow to be adopted among farmers because of lack of incentives, especially in terms of farmers’ revenue. In this work, we focus on farmers’ decision on conservation practices by focusing on maximizing farmer’s revenue over time under uncertainty. We find farmers’ optimal choices on conservation practices which maximize their revenues including revenue from selling crops and from incentives for conservation practice adoption. In addition, we also show how uncertainties of revenue change the adoption of conservation practices. Given this kind of uncertainty in revenue, each year, farmers maximize their expected revenue by choosing between a continuous crop and rotation cropping system. In our preliminary simple model, the results show that crop rotation emerges as an optimal choice in a stochastic dynamic decision problem even when agronomic effects of crop rotation are not included in the model and due solely to optimal response to revenue uncertainty. Within the same stochastic dynamic optimization framework, we include the decision on whether to adopt new conservation practices which also introduce uncertainty in farmer's decision. This uncertainty can be direct, represented by uncertainty associated with a cost of adopting a new conservation technology, or uncertainty in benefits (stemming from either the purported private agronomic benefit or from a potentially uncertain government payment), or both. Indirect uncertainty can arise even when the engineering installation cost and benefit known with certainty, as farmers may be required to give up some private crop revenue, which is uncertain. We plan to develop this optimization model to calculate critical willingness to accept for adoption of conservation practices and find socially optimal policy schemes. In addition, we will also show how the optimal crop choice and adoption of conservation technology changes under various revenue paths, especially including unexpected intense shocks.

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Conference Papers and Presentations

1. Yongjie Ji, Sergey Rabotyagov and Catherine L. Kling. "Crop Choice, Rotational Effects and Water Quality Consequence in the Upper-Mississippi River Basin: Connecting Environmental Assessment Tools with a Dynamic Land Use Model" poster presented at the

2015 Annual Meeting of Association of Environmental and Resource Economics, San Diego, CA, June, 2015.

2. Yongjie Ji, Sergey Rabotyagov and Adriana Valcu-Lisman. "Estimating Adoption of Cover Crops Using Preference Revealed by a Dynamic Crop Choice Model" will be presented at the 2015 Annual Meeting of Agricultural and Applied Economics Association, San Francisco, CA, July, 2015.

Future Research (2015–2016)

1. Land Use Modeling with Different Land Use Datasets

In addition to the Cropland Data Layers, National Resource Inventory provides another rich set of historically, spatially detailed land use data. Due to different data collection methods and standards, these two data sets give different counts on local land use information. In this work, we intend to assess whether this discrepancy will generate significant economic implications under different land use modeling frameworks. A positive answer to this question would highlight the problem in a data-richer era about careful choosing an appropriate data set in their studies.

2. Modeling Conservation Practices with County Level Observational Data

Lack of spatially detailed observational data on farmers' adoption on conservation practices, such as cover crops, limits the prediction power of the crop choice model solely relying on observed crop choice data. With the 2012 Census of Agriculture, the first county level summary information about several conservational practices are reported, such as cover crops and no-tillage. In this study, we would use the BLP method (Berry et al, 1995), a widely used econometric method in the industry organization (IO) literature, to model this county-level data. This work will shed light on the relationship between the adoption of conservational practices at county level with other local factors, such as soil conditions, local weather patterns and local farmers' characteristics.

3. Further work on modeling adoption of conservation technologies using a real options approach

We plan to modify the existing model to investigate critical adoption thresholds using both "working land" (consistent with continued agricultural production) and "land retirement" (requiring foregoing agricultural production on all on fraction of land) agricultural conservation technologies. As described above, we will introduce both direct and indirect uncertainty into such decisions. In addition, we will also show how the optimal crop choice and adoption of conservation technology changes under various revenue paths, especially including unexpected intense shocks. Model results can provide optimization-based estimates of costs of adoption, which we expect to serve as inputs in spatial optimization work.

4. Incorporating Land Use Model and Real Options Model Results into Spatial Optimization

Previously, we developed simulation-optimization heuristics to efficiently allocate agricultural conservation activities across watersheds (using SWAT and evolutionary algorithms). One concern is that optimizing these kinds of systems is subject to exogenous shocks not under the control of a decision-maker or planner. Notably, weather or market shocks could have a significant impact on the efficacy and efficiency of solutions discovered. One concern is that a solution developed under one set of exogenous parameters (a climate regime, or a cropping pattern) may not be efficient under a different set of exogenous shocks. This is the lack of robustness concern (note that it's different from the concern that a distribution of exogenous shocks maps itself into the distribution of environmental outcomes and thus the attainment of any particular goal is fundamentally uncertain—concern over 'resilience' of solutions). Further note that the variation in exogenous factors can be large. We will continue building a robust optimization evolutionary algorithm which can 1) quantify the efficiency of a particular spatial solution with respect to exogenous shocks and 2) may increase the speed with which good approximations to optimal Pareto-frontiers are discovered. We expect to use estimates of costs of adoption from the real options model as inputs into optimization and the results of crop choice models as one dimension of exogenous shocks. The policy rationale is that one can expect that public control over conservation practices (or incentives for adopting such practices) is more likely that control over crop choices which is more likely to be influenced by broader market forces and agricultural policy at the national scale.