WSC REACH Progress Report for 2012–2013

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Research from previous support (2012–2013)

Our research efforts over the past year have concentrated on four main areas: (1) precipitation and streamflow extremes under climate and human-induced change, (2) river network structure and transport for long-term predictive modeling of nutrient and sediment to inform management decisions, (3) river morphodynamics in terms of tracer dispersal in rivers and changing planform morphology, and (4) integrative predictive modeling of river hydro-geo-biological processes with emphasis on the effects of sediment change to riverine health. Application of the developed frameworks is performed in the Minnesota River Basin (MRB), which is the focus of the REACH project. However, the developed frameworks are general and transferable to other sites.

1. Precipitation Extremes and Change

It has been amply documented that streamflows in the MRB have increased considerably over the past several years, in fact, after about 1970's [*Novotny and Stefan*, 2007]. This change has been observed in the whole frequency distribution of daily streamflows with much more spatially variable change in the low quantiles (low flows) and of the order of a factor of 0 to 5 and more spatially consistent in the high quantiles (high flows) and of the order of a factor of 1.6 to 2 [*Dadaser-Celik and Stefan*, 2009]. At the same time, some changes in precipitation extremes have also been observed with a general tendency for more intense shorter duration storms during the spring and summer. Disentangling human-climatic factors of streamflow change is an issue of significance [*Schottler et al.*, 2013] when considering the future of the MRB agricultural development and practices.

In this project we seek to answer the following questions: (1) Are precipitation patterns in MN changing? If so, to what extent (amplification of extreme storms, duration of wet and dry periods, frequency of extremes)? Can we characterize this non-stationarity concisely such that we are able to take advantage of the past long data records for future predictions; (2) What useful information can we get from General Circulation Models? Is there agreement in GCMs as to future precipitation projections in the Midwestern US? What are these projections? How can we generate small-scale features of precipitation (relevant for watershed modeling) from the large-scale GCM projections consistent with the observed changes in extreme storm characteristics?; and (3) How much is the effect of this change on the streamflow? How much does precipitation change contribute to the observed amplification of stream flows vs. the amplification that comes from tile drainage? The average annual precipitation (rainfall plus the water equivalent found in snowfall) in Minnesota ranges from nearly 18 inches (457.2 mm) in the far northwest to more than 32 inches (812.8 mm) in the southeast.

This research is still in progress and results will compiled and reported in the second year report.

2. River Network Structure and Transport

2.1. River Network Analysis

The characterization of a river network via its topological properties allows one to quantitatively describe the link between network properties and hydrologic, geomorphic, and climatic variables. The Tokunaga Self-Similar (TSS) tree is one of the common representations of the hierarchical structure of river networks, which is basically a two-parameter class of trees specified by parameters a and c. Parameter a (= T_1) is the mean number of tributaries of k-order branches (Y_k) that drain into streams of order $k+1$ (Y_{k+1}) and expresses "*first order hierarchy*", while parameter c (= T_k/T_{k-1} , $k \geq 2$) is the ratio of two consecutive Tokunaga tree generators and expresses the "*higher order hierarchy*" [*Zaliapin et al.*, 2010]. Tokunaga parameters are important descriptors of river networks; their values and range of variability are yet to be explored for river networks in the Minnesota River Basin (MRB).

In order to derive the mentioned Tokunaga parameters for different sub-basins in the MRB, we have analyzed the existing 12 watersheds by extracting the stream network from 10m DEM and defining the area threshold of 0.1 km^2 for stream initiation. The drainage areas of the examined basins ranged from 1790.2 km^2 to 5184.1 km^2 and the Horton-Strahler orders of their stream networks are of orders 7 and 8. The estimated Tokunaga parameters of the river networks in the MRB are shown in Figure 1. The a values range from 1.02 to 1.13 and the c values from 2.07 to 2.62. The variability in a is less than that of c, with its standard deviation more than two times lower than that of c (see Table 1). We observe lower c values for rivers in the upstream such as the Headwaters, Pomme de Terre, and Chippewa Rivers. This is consistent with the climatic dependence obtained by *Zanardo et al.* [2013] as the upstream watersheds in the MRB experience less rainfall than those in the downstream. There are no significant differences between the a and c values of rivers with Strahler order of 7 and 8.

Table 1. Mean and Standard Deviation (in parenthesis) of the Estimated Tokunaga Parameters a and c for the 12 Watersheds in the Minnesota River Basin.

Max Stream Order	*a*	*c*
Oder 7	1.06 (0.02)	2.44 (0.22)
Oder 8	1.06 (0.04)	2.45 (0.10)

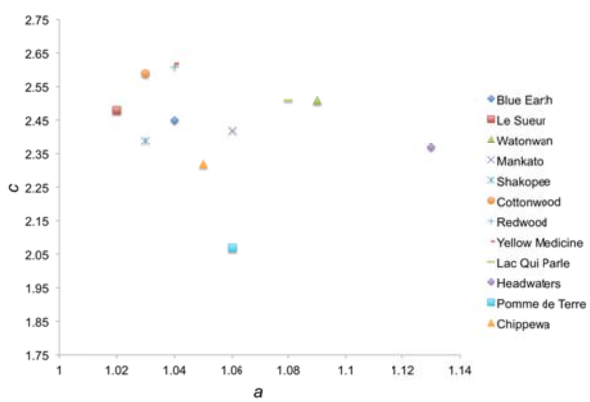

Figure 1. Parameter Space for the Estimated Tokunaga Parameters a and c for the 12 Watersheds in the Minnesota River Basin.

2.2. Sedimentological Response

Long-term prediction of environmental response becomes highly uncertain using physically-based distributed models, particularly for the sedimentological response for sand and gravel, with time scales ranging from tens to thousands of years. Yet, such predictions are needed as changes in one part of a basin now might adversely affect other parts of the basin in years to come. We have proposed a simplified prediction framework which takes advantage of network topology, channel characteristics, and transport-process dynamics and offers the possibility to identify hot spots or vulnerable areas/times of disturbance that can lead to synchronization and downstream amplification of the sedimentological response [*Czuba and Foufoula-Georgiou*, submitted]. The proposed framework relies on performing a process-based scaling of the river-network width function to a time-response function (travel-time distribution). We have developed the process-scaling formulation for transport of mud, sand, and gravel and applied the methodology to the Minnesota River Basin.

The process-based scaling of the Minnesota River network unexpectedly transformed the network width function into a sand response function exhibiting two peaks, which arose from network topology, channel morphology, and sand-transport formulation. The two prominent peaks suggest that there is a resonant frequency of sediment supply that would lead to a downstream amplification of the observed sedimentological response. The peaks of the response can be attributed to specific areas of the basin, highlighting that the disturbance of one region followed by the disturbance of another region after a certain amount of time, results in an amplification of the effects of the sediment inputs that is otherwise difficult to predict (Fig. 2). The amplification of the sedimentological response would result in greater than expected aggradation of the bed of the river leading to disruption in ecosystem function, increased flood risk, and increased cost associated with remediation. Therefore, the proposed framework has identified an important vulnerability of the Minnesota River Basin to spatial and temporal structuring of sediment inputs, and can aid in understanding how current and future management decisions will be superimposed on the evolving landscape as it responds to past disturbances.

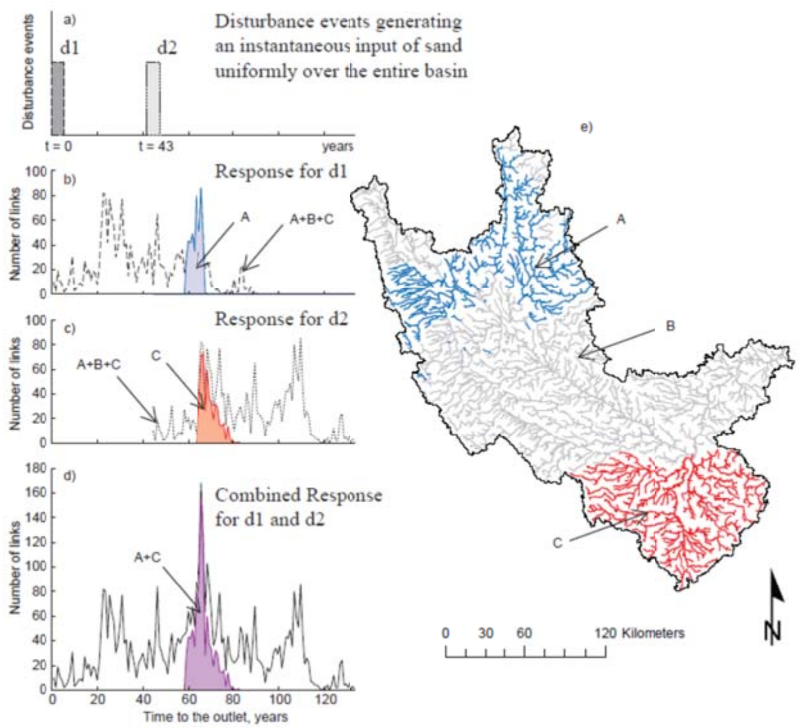

Figure 2. Synchronization of sediment fluxes can lead to amplification of the response for the Minnesota River Basin. (a) Disturbance of the landscape leading to two instantaneous inputs of sand (0.1 mm; uniformly over the basin) at 0 years (disturbance 1 or d1) and 43 years (disturbance 2 or d2). (b) Sedimentological response for d1; entire basin response [dashed line; basins A+B+C in (e)] and region corresponding to the second peak of the sand response [blue shaded area; basin A in (e)]. (c) Sedimentological response for d2; entire basin response [dotted line; basins A+B+C in (e)] and Blue Earth River Basin [red shaded area; basin C in (e)]. (d) Superimposed response for sand [sum of (b) and (c)] into an observed response (black line) resulting in amplification of the effects of the sediment inputs. Amplification can also occur if only the regions contributing to the peaks of the response [basin A in (b) and basin C in (c)] are disturbed and responses superimposed [purple shaded area; A+C]. (e) Partition of the basin into 3 regions: the region corresponding to the first peak of the sand response (red; C, Blue Earth River Basin), second peak of the sand response (blue; A), and the rest of the basin (gray; B).

3. River Morphodynamics

3.1. Sediment/Tracer Dispersal

Understanding the transport of tracers (e.g., sediment particles on which pollutants or nutrients are attached) is a problem of significant theoretical and practical interest for which, however, little understanding exists in non-plane bed rivers, i.e., in the presence of bedforms. A series of controlled experiments were conducted at a large flume the St. Anthony Falls Laboratory to study the effect of varying discharge on bed topography and tracer dispersal. Instantaneous, high-resolution bed elevations and sediment transport rates along with travel distances of tracer particles of size representative of the grain size distribution of bed material were measured, for a range of discharges (see schematic in Fig. 3). We show that bedform geometry directly depends on discharge with increasing height, decreasing length, and decreasing variability in bedform aspect ratio as the discharge increases. For the case of higher discharges where the bed topography is more pronounced, it is demonstrated that the length of the bed forms acts as a first order control on tracer travel distances. Based on a multi-scale analysis of bed elevation increment series, we demonstrate that the spectral slope and the degree of non-linear dependence of higher order structure functions on moment order control the distribution of travel distances, with larger particles traveling further at low discharge and smaller particles not significantly affected by the discharge rate. Results also show that the mean travel distance of smaller particles does not get much affected by the bed topography as the dynamics of smaller particles are mainly dominated by the particle hiding effect (see Fig. 4). Our results also confirm, for the first time, the heavy-tailed distribution (truncated power-law tail) in the statistics of tracer travel distances for a mixture of grain sizes and discharges as recently hypothesized in theoretical studies and as expected in natural rivers characterized by a wide grain size distribution and extreme flood events (see Fig. 5). The implications of these results for predictive modeling of sediment transport are being explored.

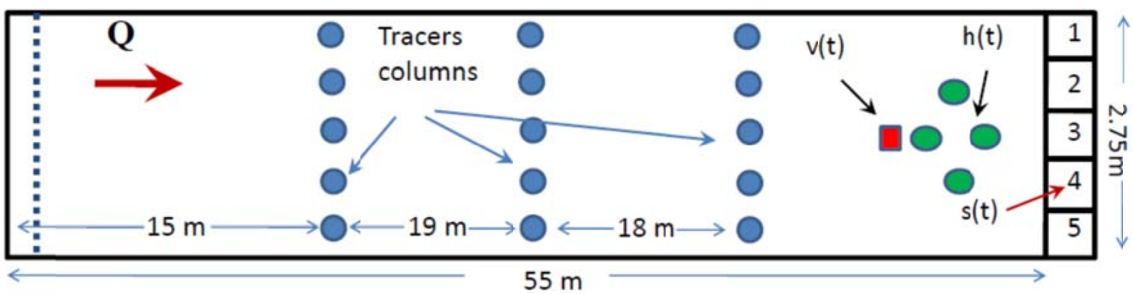

Figure 3. Schematic of the experimental setup showing the locations of sonars (used for measuring temporal bed elevation h(t)), the ADV (used for measuring velocity fluctuations v(t)) and the pans (used for measuring bedload transport s(t)) at the downstream end of the channel. Fifteen tracer columns were installed in the bed for measuring the entrainment rate of the particles. The flow direction is from the left to the right of figure. The dash line at the upstream end of the channel represents the location of the paramagnetic tracers introduced at the end of the run.

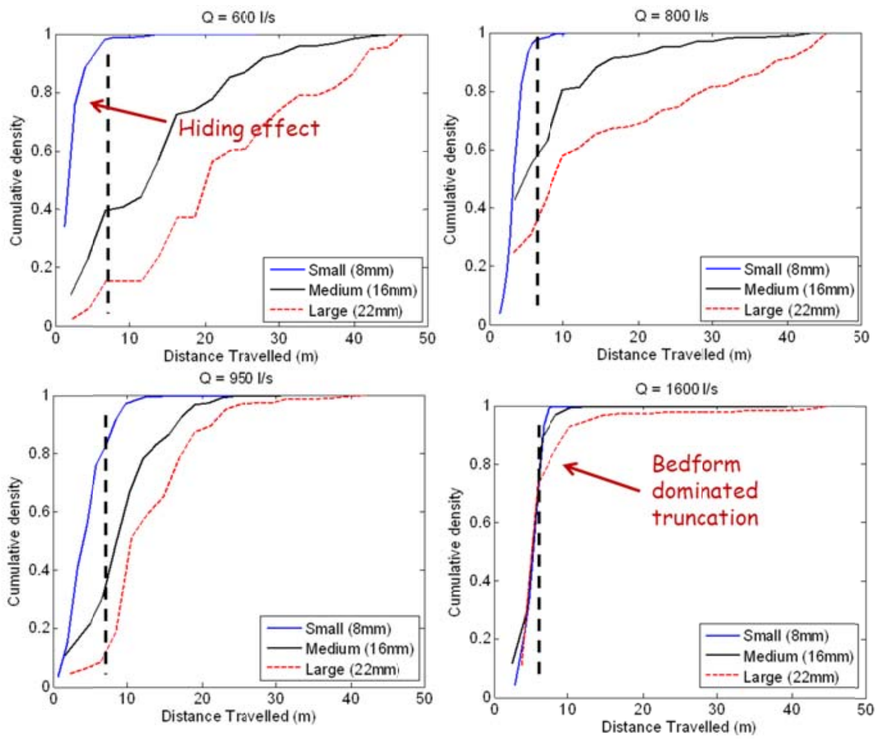

Figure 4. Cumulative density functions of tracer travel distances for the discharges of 600 l/s (top left), 800 l/s (top right), 950 l/s (bottom left), and1600 l/s (bottom right). Note that at low flows (e.g., 600 l/s), for approximately plane bed, the transport of sediment is selective whereas at high flows (e.g., 1600 l/s) where the bed forms are more pronounced equal mobility of sediment is observed.

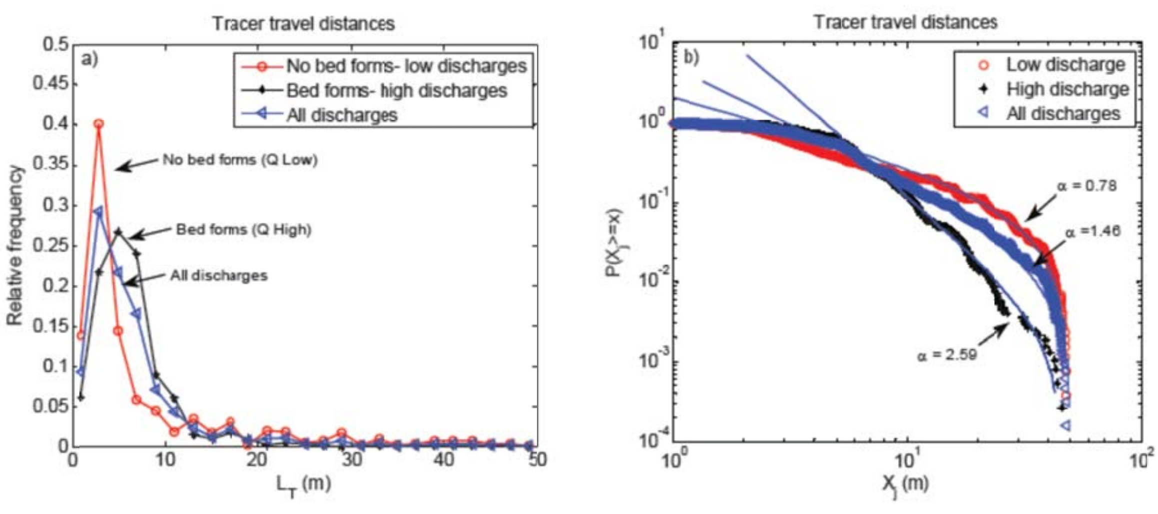

Figure 5. a) Probability density functions, and b) probability of exceedance of travel distances for the mixture of tracer particles for low discharges (open circles), high discharges (stars) and for all discharges (open triangles). Truncated Pareto distributions are fitted to these exceedence probabilities with parameters as indicated in the Figure.

4. Integrative Hydro-Geo-Biological Predictive Modeling

Climate change and widespread changes in land use (agriculture and urbanization) over the past century have altered streamflow and sediment dynamics, leading to ecological impairment of stream ecosystems. Excessive sediment loading negatively affects fish and other aquatic invertebrates primarily through habitat degradation, but also by inducing physiological stress and reducing feeding and growth rates, among others [*Newcombe and Jensen*, 1996; *Wood and Armitage*, 1997; *Blann et al.*, 2009]. These alterations in stream dynamics have greatly affected the abundance and diversity of freshwater mussel species, which are now considered as the most endangered freshwater fauna in the United States with 70% considered endangered, threatened, or of special concern [*Williams et al.*, 1993; *Stein et al.*, 2000]. Understanding the processes and feedbacks involved between streamflow, sediment, and biota is essential for formulating management measures and in the remediation of imperiled river ecosystems. Although untangling the dynamic feedbacks of the coupled hydro-geo-biologic system seems daunting, a necessary first step is to focus on the interactions of the major variables we believe to be driving the dynamics of the system.

Assuming sediment-related factors are the strongest limiting factor of mussel populations, we propose a model for predicting mussel populations where process interactions, that include the generation of sediment and effects on biota, are driven by a time series of streamflow (Fig. 6). The process interactions capture the major features (nonlinearity, thresholds, etc.) of actual process dynamics. The interaction framework can serve as a skeleton for future refinements that incorporate additional interacting variables and process dynamics. Our simple process-based model provides (1) a better predictor of mussel populations than can be predicted by geomorphic/hydraulic variables (upstream drainage area, slope, 2-year recurrence interval peak streamflow, depth, width, cross sectional area, velocity, and Froude number) and (2) a simpler (to obtain) diagnostic of mussel populations than provided by more complex models [see *Beadman et al.*, 2002]. We are applying the model to the Minnesota River Basin, which has experienced significant changes in precipitation and runoff, increased sediment delivery, and decreasing mussel populations, to determine (1) how climate and land-use change may undermine the resilience of mussel populations and (2) how management efforts, i.e., creating more wetlands or slowing the flow from agricultural drain tiles to rivers in order to reduce peak flows, can propagate through the coupled hydro-geo-biological system to allow mussel populations to recover. Preliminary results indicate that the developed model is able to capture the dynamics of the system and provides a useful tool for evaluating management scenarios.

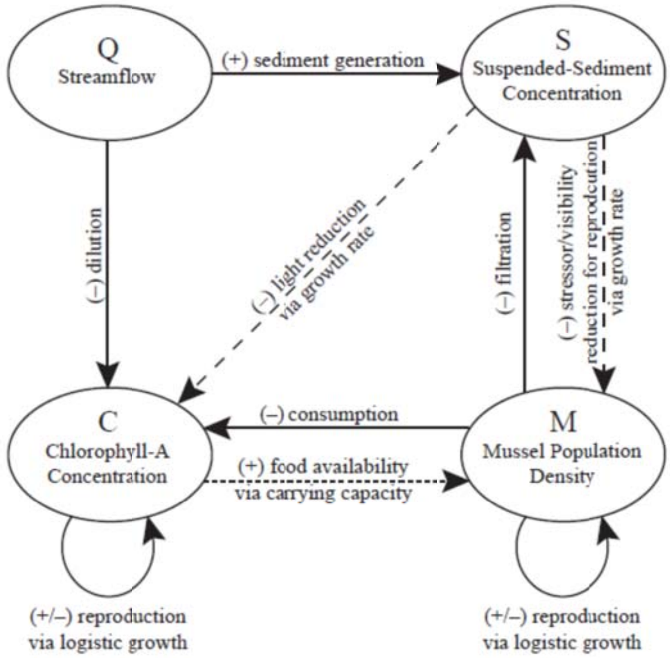

Figure 6. Interaction framework between the major variables driving the dynamics of the coupled hydro-geo-biological system. Streamflow is the main driver of the system, generating suspended sediment and diluting the concentration of chlorophyll-A. The other three variables interact as follows: suspended-sediment concentration reduces the birth rate of both chlorophyll-A and mussels; chlorophyll-A concentration reduces the carrying capacity of the mussel population and self reproduces; mussels filter suspended sediment, consume chlorophyll-A, and self-reproduce.

Future Research (2013–2014)

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

1. Precipitation Extremes and Change

- Document and parameterize changes in extreme daily precipitation across the Minnesota River Basin, as well as changes in the time between storms, and storm durations.
- Use non-parametric but also parametric (based on Copulas) to quantify the relation (possibly nonlinear) between the changes in precipitation extremes and streamflow extremes in selected sub-basins of the MRB.
- Study future changes in the precipitation of the basin as predicted by climate models and assess the effect of these changes in streamflow increase for different scenarios of land use and management decisions.

2. River Network Structure and Transport

- Investigate the transport of sediment (and other material) along the river network using a minimal complexity, simple predictive framework and test this against available data.
- Relax some of the assumptions of the framework related to storage and release of sediment in the system.
- Explore the scaling structure of the different sub-basins of the Minnesota River Basin and relate their self-similar topological structure to the underlying geologic history.

3. River Morphodynamics

- Understand how the natural meandering of rivers in the basin 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.
- Continue to study tracer dispersal in the presence of bedforms via experimental and field work.

4. Integrative Hydro-Geo-Biological Predictive Modeling

- Further test and validate the developed model of water-sediment-stream biology using data from several sub-basins of the MRB.
- Relax some of the model assumptions and also more rigorously incorporate effects of scale discrepancy between the micro-scale at which processes occur and the macro-scale at which observations are available.

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WSC REACH Progress Report for 2012–2013

Jacques Finlay's group

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Ongoing and future research

Our research efforts over the past year have concentrated on four areas targeted to provide information to develop empirical and predictive models of landscape and climate change impacts on stream structure and processes: (1) data synthesis to identify drivers of variability in watershed nutrient export (2) examination of river network scale patterns in physical and biological structure to inform predictive modeling of nutrient transport and cycling (3) influence of wetlands on local and downstream structure and processes in stream networks, and (4) integration and support for model development to connect research elements across subcomponents. All research described below is in planning or early implementation, and results presented should be considered preliminary.

1. Watershed nutrient dynamics

Water quality impairment in the Minnesota River Basin (MRB) basin has been recognized as a major regional issue for decades, leading to the implementation of intensive monitoring programs by USGS and state agencies (Minnesota Pollution Control, Department of Natural Resources, and Department of Agriculture; respectively, MPCA, MDNR and MDA). Changes in precipitation, temperature, drainage, and crop cover (described elsewhere in this report) all influence watershed nutrient export (Dubrovsky et al. 2010). We are working to synthesize available data towards understanding the relative influence and potential interaction of these facto in the MRB, and generating hypotheses for field work in subsequent years. Using the relatively rich monitoring databases for large scale nutrient monitoring, we seek to answer the following questions:

(1) Is there a temporal or spatial scale at which in-stream ecological processes have a significant effect on nutrient flux?
(2) Are there land use signatures on nutrient export?
(3) Is there hysteresis in nutrient losses in response to climate variability (dry vs. wet years)

In-stream nutrient uptake in large rivers has long been assumed to be negligible, although recent work has cast some doubt on this earlier assumption (Tank et al. 2008). By comparing matched data records for two monitoring sites we have quantified nitrate reduction within this reach of the Minnesota River over a 30 year time period (Fig. 1). From this data, it is evident that, at least for this reach, in-stream nitrate uptake is significant in some years in August and September. However, in years when uptake is significant, all available nitrate can be removed within the reach.

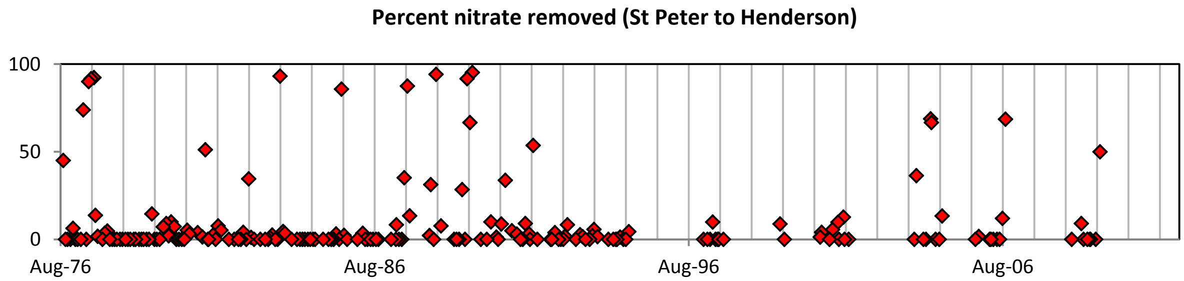

Figure 2. Percent of nitrate measured at St. Peter monitoring station that was removed in reach. Sizable in-stream nutrient uptake occurs in Aug-Sept some but not all years.

In order to understand downstream contributions from individual sub-basins we examined multiyear load data available from MPCA. For example, the Chippewa River basin, has a similar water runoff volume per watershed area to the rest of the basin but contributes significantly less nitrate load than the other basins (Fig. 2). Total suspended solids (TSS) for the Chippewa River basin are similar to the rest of the Minnesota River watershed. Future work will explore how climate, land use or agricultural practices in the Chippewa River basin are reducing nitrate losses from this watershed.

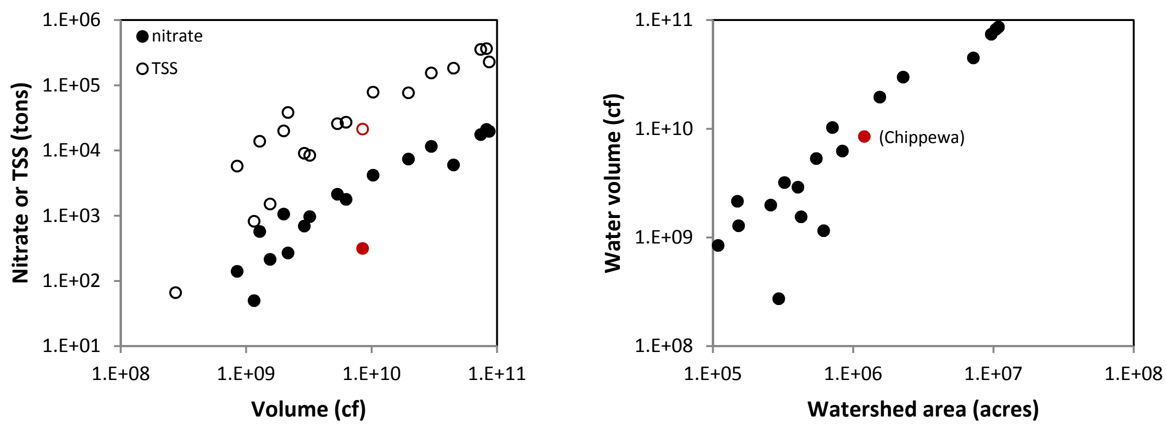

Figure 2: Approximate annual load (i.e.ice out through September) versus runoff volume (A) and watershed area (B) data from MPCA. Each point represents a major sub watershed of the MRB with similar land cover and total nitrogen (TN) inputs. TN input (from fertilizer, N fixation and manure) explains almost no variation in watershed N loss; variation in losses is largely driven by differences in precipitation and runoff. The Chippewa River sub-basin (show in as a red circle) contributes much less nitrate loading compared to other sub-basins although annual runoff per watershed area is similar.

One question, important for model development and for understanding nutrient loading and uptake, is whether the response of the system to discharge is time invariant or if there is a hysteresis or system memory of past conditions that influences the functional relationship of nutrient concentration. If this is a significant factor, then understanding the effects of past nutrient loading and discharge is critical. Wet years following dry years typically export more nitrate than expected due to storage within the upland soil as a result of soil mineralization (Kane et al. 2008). From analysis of the monitoring record for the Minnesota River at Jordan, we see that this effect may stretch out for multiple years (Fig. 3). For example, in both 1982 and 1992, discharge continued to increase but bioavailable nitrogen for nitrification appears to be exhausted and nitrate concentrations decrease.

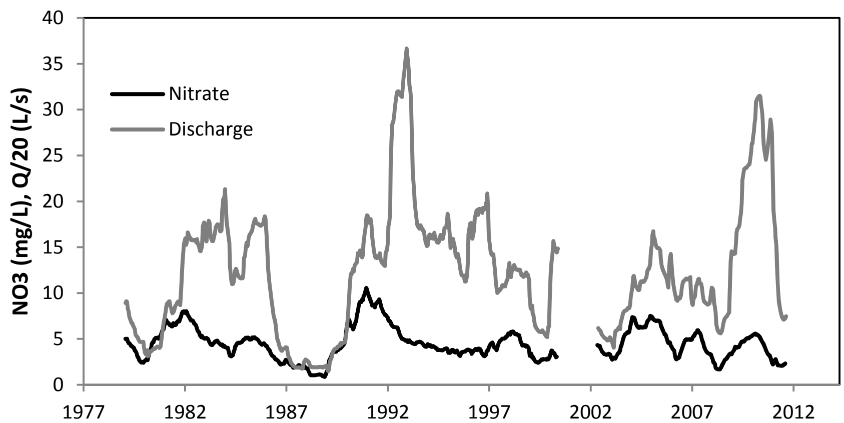

Figure 3 One year running averages of nitrate and discharge at the Jordan monitoring station on the Minnesota River. Data shows periods of time when discharge is increasing, nitrate originally increases then decreases despite continuing increasing in discharge (e.g. 1982-1985, 1992-1994).

2. River Network Structure and Processes

Climate change and widespread changes in land use over the past century have altered stream hydrology, nutrient loading and in-stream sediment dynamics, often to the detriment of stream ecosystems (Allan 2004). In agricultural systems, these three impairments are tightly coupled. There is limited current understanding of the relative contribution of each to overall ecosystem functional degradation. Excessive sediment loading may alter stream metabolism and ecosystem functioning by decreasing light availability and decreasing habitat stability (Sheldon et al. , Burdon et al. 2013). Excessive nutrient loading may stimulate planktonic production, further decreasing light availability at the benthos. Insufficient supplies of carbon, due to farmed riparian zones and dredged ditches, can limit primary productivity in ditches. Recent research shows that river ecosystems in agricultural watersheds exhibit a wide range of biotic responses to human activities both within a site through time, and across sites. Although understanding of dynamics in human dominated catchment is increasing, we still lack information to predict how specific changes in land cover and climate will affect biological processes. Through field measurements and analysis of the long term data set we are exploring the interactions of discharge, suspended sediment, organic material availability, light attenuation and nutrient availability on ecological function and processes. As a starting point, our field based measurements for the current season have been within the Le Sueur river basin network, where sediment sources have been carefully delineated (Belmont et al. 2011, Maalim et al. 2013).

Work begun in 2013 seeks to identify relationships between physical features (such as flow, slope, suspended sediment, light) on biological processes in agricultural drainage networks. A substantial long term monitoring record provides much insight into physical variable behavior in larger rivers but little data is available detailing physical relationships within tiles, ditches and small streams in an agricultural system. Our intent this summer is to quantify the contributions of these smaller components of the network in order to inform our understanding of current system ecological functioning, potential sources of resilience (such as wetlands) and aid our colleagues modeling efforts.

Initial field measurements of physical variables are largely exploratory in nature and aim to answer the following questions:

1. Is there a scale invariant relationship between discharge and suspended sediment concentration, discharge and nutrient concentration or suspended sediment concentration and light decay?
2. Is the response of benthic biological processes to light, nutrient and carbon limitation a threshold response or continuous response? Can we describe this response as a variable dependent on discharge or watershed area?
3. How do upstream wetlands and lakes modify water chemistry and physical properties?

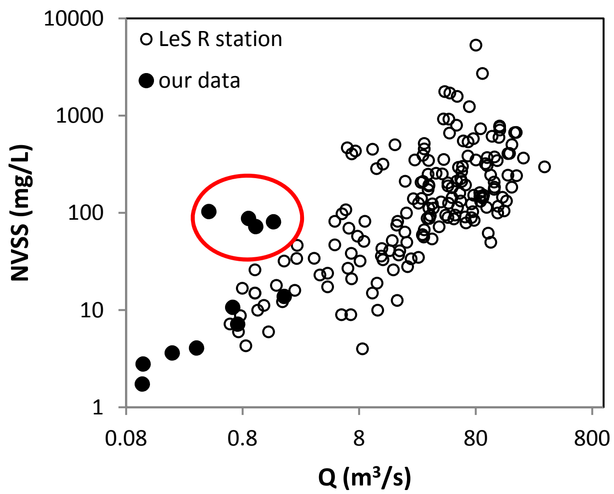

Figure 4 Relationship between discharge and non-volatile suspended sediment from Le Sueur River monitoring station time series (LeS R, open circles, USGS station ID 05320500, 2004-2008) and spatially variable data taken by our team in tributaries (closed circles, Le Sueur River basin, summer 2013). Four points within red circle are on Cobb River and influenced by a large, eutrophic lake.

Wetlands and lakes may either add system resilience (by dampening storm streamflow response, providing low oxygen locations where denitrification can occur, stable environment so more aquatic vegetation i.e. carbon source, and deposition of sediments) or may increase system vulnerability by providing a source of phytoplankton and phosphorus to lower reaches. Some locations in the MRB, such as the Chippewa and Pomme de Terre Rivers, offer some evidence of intact ecological processes and functioning. These sub-basins also have more upland storage capacity, due to extensive remnant wetland and lakes. All data (excluding the data downstream of a lake) show the relationship of TSS to discharge is invariant across space (our sampling sites) and time (monitoring data from the Le Sueur River) (Fig. 4). Further sampling to support this observation will be gathered through future site monitoring efforts.

3. Influence of wetlands and lakes

The restoration (or creation) of wetlands and ponds in heavily-drained agricultural landscapes has been shown to yield beneficial ecological effects, including N removal and biodiversity enhancement (Hefting et al. 2013). Increased wetland cover in such landscapes would add additional habitat and water storage capacity, leading to range of potential benefits (Strand and Weisner 2013, Tomer et al. 2013). However, little is known about how the location of wetlands (i.e., longitudinal position in the stream network, density of wetlands per stream mile) or their various characteristics (i.e., soil type, storage capacity, plant community type, etc.) might variously contribute to the enhancement of biodiversity and/or the resilience of aquatic stream communities.

We are evaluating the local and longitudinal effects of wetlands on stream biodiversity and trophic structure, with consideration to the placement and characteristics of restored wetlands. Preliminary data collection ongoing in summer of 2013 uses the Le Sueur River basin as a model system. These efforts include collection of macroinvertebrate samples from stream sites located up- and downstream from both individual wetlands and wetland complexes (i.e., multiple wetlands located in series). We will use these samples to evaluate 1) macroinvertebrate diversity, and 2) the trophic structure of macroinvertebrate communities (using stable isotope analysis). This sampling is occurring in conjunction with analysis of in-stream water quality (N, P, TSS, etc.) and in-stream habitat, with the goal of determining whether variation in macroinvertebrate diversity or trophic structure can be linked to wetland-mediated changes in stream condition. Depending on the results of these preliminary data, future data collection efforts may expand to include additional stream communities (e.g., fish, amphibians), or more detailed characterization of different wetlands and their effects on stream communities. Finally, we intend to work with data from MPCA's biological monitoring program -- including macroinvertebrate, fish and habitat data for sites throughout the Le Sueur basin – to help identify relationships between land use, characteristics of stream networks, and biodiversity.

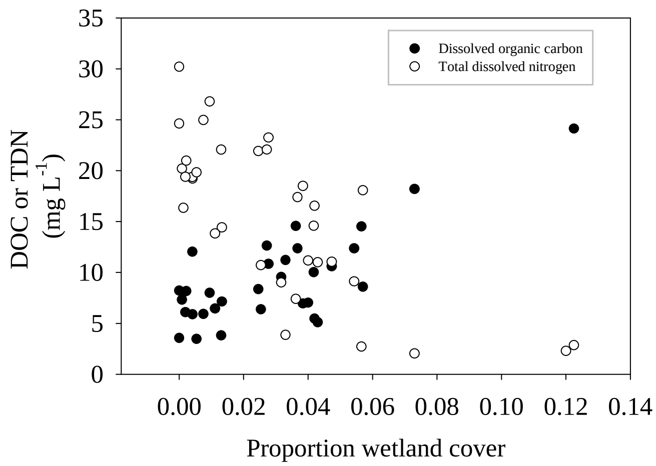

Figure 5 Relationship between cover of remnant wetlands and DOC and TDN concentrations during spring conditions of peak nitrate loss in the LeSueur, Cobb, and Cannon Watersheds. Watershed sizes ranged from 4 to 4000km^2. Note 80-90% of TDN is as NO_3-N.

Parallel with efforts to under effects of wetland on stream ecosystem structure, we are examining the role of wetlands in local and downstream water quality. Data collected across a gradient of wetland cover and basin size during periods of maximum nitrate flux show that relatively small areas of riparian wetlands can substantially reduce N loads, and increase organic carbon availability to stream ecosystems (Fig. 5). Data will be used to interpret existing water quality patterns in the MRB (see section 1) as well as develop tools to assess the potential for wetland creation to improve water quality in the basin (Passy et al. 2012).

4. Integrative Model Development

Work has initiated to develop a watershed model of the Minnesota River Basin to support various aspects of the broader project. Lead by Dalzell, several REACH PIs (Belmont, Kling, Finlay, Rabotyagov) as well as the watershed modeling group at CARD (Iowa State, who are working on a larger model of the entire Upper Mississippi River Basin) are establishing a framework for model development efforts that are complementary among multiple projects components. Development of a model specific to the Minnesota River Basin is planned for linking economic analyses to river nutrient processes. Initial model efforts will focus on:

1) Establishing a framework to more accurately represent flow and sediment routing from multiple sources in the model environment. These efforts will allow inclusion of wetland and lake cover in analyses of past

conditions (informed by existing data) as well as examination of a range of scenarios for future land cover and climate conditions.

2) Provide important information about landscape productivity and ecosystem services that can be used for economic full cost accounting analyses.

Collection and formatting of basic model inputs has begun and efforts are ongoing to develop a model of the Minnesota River Basin that will provide value to the greatest number of project participants.

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WSC REACH Progress Report for 2012–2013

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University of Minnesota Duluth Geological Sciences

Previous Research:

Our research group has focused on understanding how landscape evolution affects modern sediment loading in recently deglaciated basins. Understanding the role of geomorphic history on modern "hot spots" of erosion allows for prediction of hot spot locations and how they may be exacerbated by changing climate or land use. While most of this previous research has been carried out in the Minnesota River basin (primarily the Le Sueur watershed), we have also worked in incised rivers along the North Shore of Lake Superior, close to the Duluth campus of the University of Minnesota, to allow for more detailed monitoring of erosion and channel change at the event scale. Our primarily field- and GIS-based analyses complement numerical model development by colleagues on the REACH project.

Current Research:

1. Sediment budgeting and scaling of modern erosion rates across watersheds

Understanding how climate change affects erosional hotspots and drives ecological response requires knowledge of modern erosional hot spot locations and rates of change. Previous research in the Le Sueur watershed (Belmont et al., 2011; Gran et al., 2011), has found four dominant sediment sources: bluffs, ravines, streambanks, and upland fields (primarily low-gradient to flat agricultural fields). Rates of erosion were determined over annual to decadal timescales for each source using multiple overlapping approaches including historic aerial photo analyses, geochemical fingerprinting, terrestrial laser scanning, and analyses of aerial LiDAR topographic data. This work not only pinpointed source type and rates of erosion, but also showed that most fine sediment in the Le Sueur watershed was sourced from near-channel sediment sources (bluffs, streambanks, and ravines) in the deeply-incised knick zones in the lowermost valleys. These areas represent the natural erosional hot spots that we hypothesize experience the greatest rates of change under conditions of changing climate and land use. The spatial location of erosional hotspots relates strongly to the geomorphic history of the basin, in which upstream-migrating knickpoints have led to deeply-incised lower valleys on most tributaries. As we move out of the Le Sueur watershed into other tributary watersheds with similar geomorphic histories, we need to determine how transferable rates and patterns of erosion are from the Le Sueur watershed to other neighboring basins, allowing the research from that basin to be more widely applicable.

This particular project focuses on determining how scalable rates and patterns of erosion are across watersheds within the same general geomorphic setting. Basin-scale variations in surficial geology, topography, and climate contribute to variable sediment fluxes, and thus act in opposition to the normalizing force that shared geomorphic history plays on sediment fluxes. To date, we have assembled a first-order sediment budget on two neighboring Minnesota River watersheds, the Blue Earth and Watonwan (see Figure 1), to compare with the more detailed budget developed on the Le Sueur watershed (Belmont et al., 2011; Gran et al., 2011). High-resolution LiDAR data were used to delineate streambank, bluff, and ravine sediment sources and determine the location of the knick point that separates a highly erosive lower valley ("knick zone") from the upper watershed (see Figure 2).

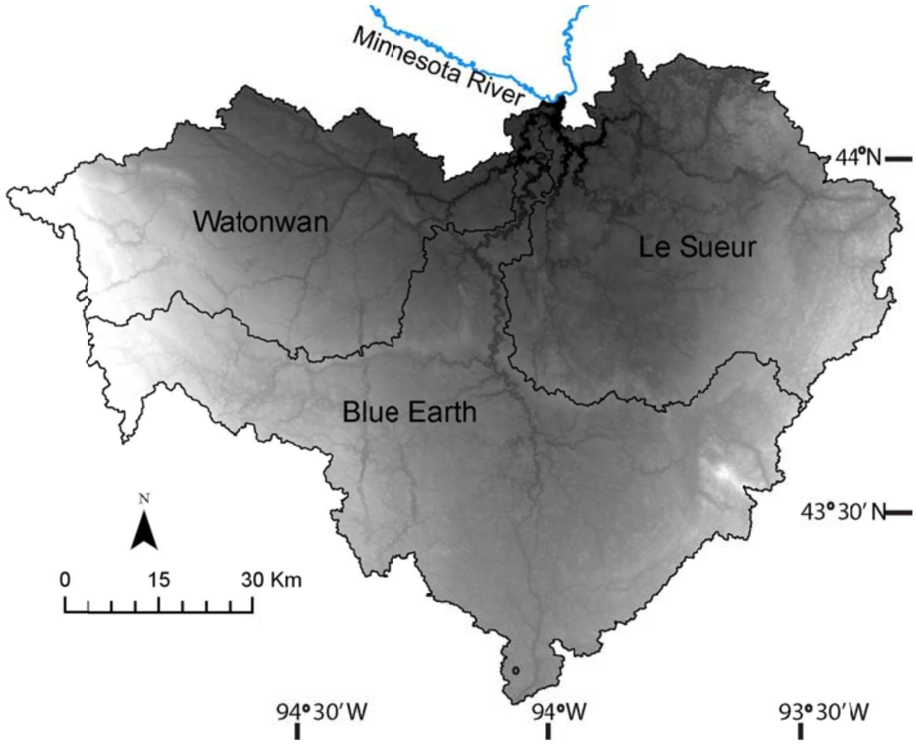

Figure 1: Location of the Blue Earth and Watonwan watersheds, with respect to the Le Sueur watershed and the Minnesota River.

We extrapolated rates of erosion from the Le Sueur watershed to the Blue Earth and Watonwan, applying them to different sediment sources based on landform and spatial location (above vs. below the knick zone). Results were compared with sediment loads determined from total suspended solids (TSS) measurements gages at the mouth of each basin. Preliminary results indicate that this first-order approach is not sufficient and that local variability has a significant effect on erosion rates. The next phase involves measuring rates of channel migration, bluff erosion, and upland erosion using a suite of tools to determine A) how rates vary across the three watersheds and B) how those variations relate to changes in surficial geology, topographic relief, and climate. Preliminary results indicate that meander migration and bluff retreat rates in the Blue Earth River are significantly higher than in the Le Sueur. Understanding why will be critical in development of mechanistic models for bluff erosion that eventually will relate flow variability to bluff erosion rates.

This project is still in progress. Results will be integrated into other REACH research projects as well as shared with stakeholders in the Greater Blue Earth River basin.

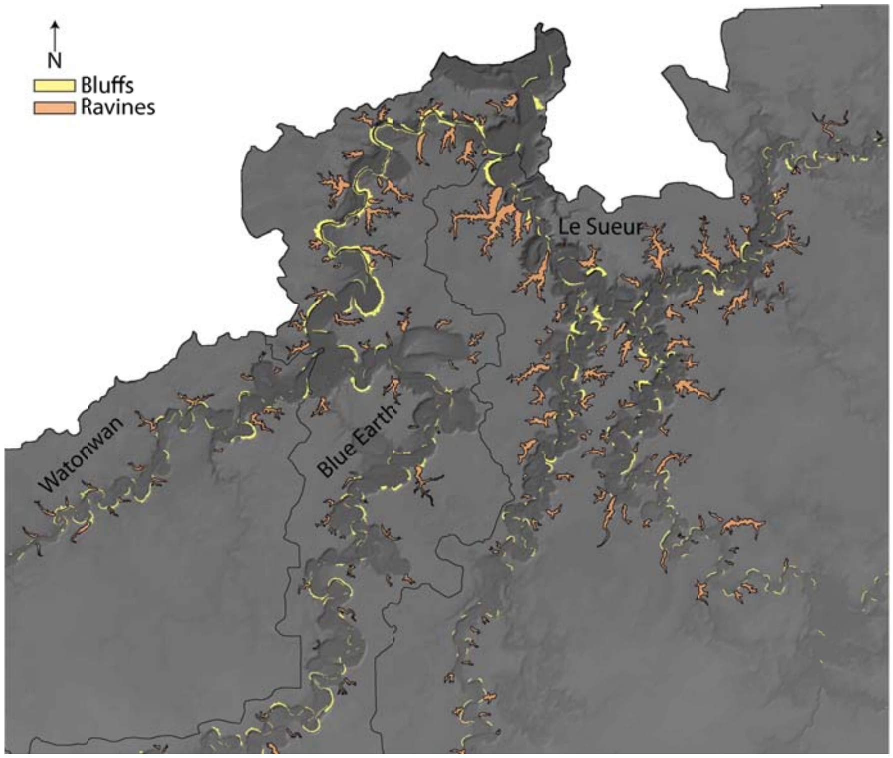

Figure 2: Bluffs and ravines mapped from LiDAR topographic data are predominantly found in the deeply-incised lower valley, downstream of knick points on major tributaries of the Minnesota River.

2. High-resolution bluff erosion monitoring

Bluff erosion contributes over half of the fine sediment load to the Le Sueur River, increasing turbidity and affecting the aquatic ecosystem (Belmont et al., 2011; Gran et al., 2011). Research into valley evolution on the Le Sueur indicates that bluff erosion rates in the modern system are approximately 3 times higher than bluff erosion rates in the late Holocene, before agriculture dominated the landscape (Gran et al., in press). Our hypothesis is that increased flows (as documented in Schottler et al. (2013) and Novotny and Stefan (2007)) are driving increased bluff erosion rates through additional shear on the toe of bluffs. However, it is unclear what aspect of increased flows is driving increased bluff erosion. Is it increased peak flows? Increased volume of flow? Or perhaps increased volume of flow above a critical shear stress? Each of these scenarios results in different management options to mitigate the increase in fine sediment loading associated with fluvially-driven bluff erosion.

Previous research in the Le Sueur watershed utilized terrestrial laser scanning (TLS), also known as ground-based LiDAR, to conduct annual to semi-annual scans of individual bluff surfaces. Geomorphic change detection techniques were developed to measure both when, where, and how much erosion was occurring on individual bluff surfaces (Day et al., 2013a). These data were then compared with decadal-scale bluff migration rates as determined from historic aerial photographs to look at potential spatial and temporal variability of a fairly stochastic erosional process (Day et al., 2013b). We collected an additional year of TLS data on the bluffs studied by Day et al., (2013a), both to extend the monitoring record an additional year and to take advantage of a unique opportunity to compare volumetric erosion rates as determined from TLS to volumetric erosion rates determined from repeat aerial LiDAR. Blue Earth County (where the study bluffs are located) had aerial LiDAR flown in both 2005 and 2012, almost perfectly overlapping with the time period of scans on the study bluffs. Colleagues at Utah State University are analyzing the repeat aerial LiDAR data, and we should be able to compare the two datasets this fall.

An additional finding of the Day et al. (2013b) TLS study is that there was a positive relationship between the volume of sediment eroded and the peak flow encountered between scans. This makes sense physically if shear stress on the bluff toe is a primary driver of bluff erosion overall. However, the time between scans was generally on the order of 6 months to 1 year (Day et al., 2013a), making direct analyses challenging. Addressing the issue of how flow magnitudes and volume affect bluff toe erosion requires A) a mechanistic model of toe erosion that can account for the roles of both peak flow rates and total volume of flow above a critical shear stress on bluff toe erosion and B) data at an individual event scale that can be used to compare with model results. Our research group has been focusing on data collection and analysis over the past year. Rather than work in the Minnesota River basin, we have been working in a basin closer to the Duluth campus to facilitate ease of access before and after individual storms. Twelve bluffs were monitored, with data collected before and after major storm events. While this work started before the REACH project began, the results are intended to be applicable to stream bluff erosion in general, with an emphasis on building a stronger understanding of the interplay between increasing flows and increasing rates of bluff erosion seen in the Minnesota River watershed (Gran et al., in press; Schottler et al., 2013).

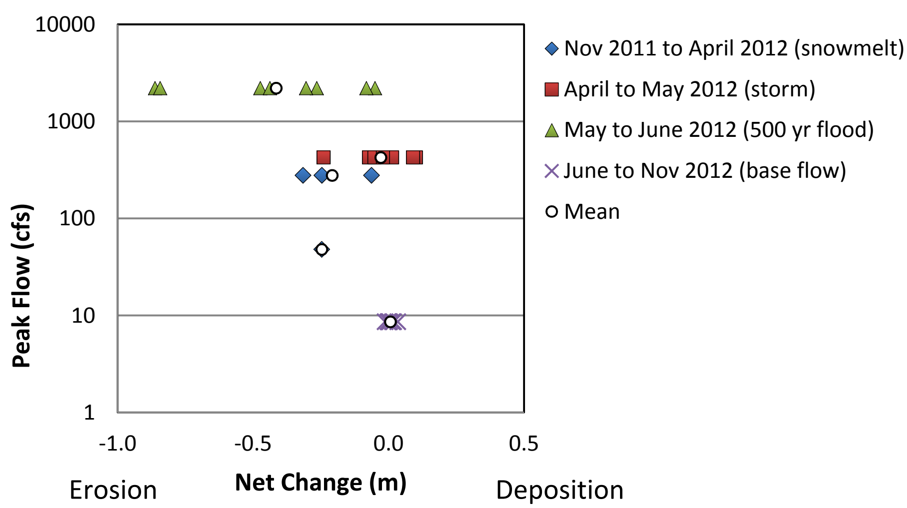

Figure 3: Bluff retreat rates (Volume/Area) for storm events (April-May 2012; May-June 2012), snowmelt (Nov 2011-April 2012), and summer low flow (June-Nov 2012). The peak discharge for the June 2012 event is preliminary and was estimated based on neighboring basins, since the gage on Amity Creek was destroyed during the June 2012 event. Each data point reflects an individual bluffs, except for mean retreat rates for each peak flow (shown with circles).

The monitoring work in Amity Creek and Lester River near Duluth, MN, shows a positive relationship between peak flow and the bluff retreat rates in individual storms and over snowmelt (see Figure 3). We are currently working on the relationship between flow volume and bluff erosion rates, which is complicated by a 500-year event that occurred in June 2012, destroying many stream gages in the region.

Future Research Plans (2013-2014):

1. Sediment budgeting and scaling of modern erosion rates across watersheds (continuing)
   - Complete sediment budgets for Blue Earth River and Watonwan River, incorporating additional measurements of decadal-scale bluff erosion rates from historic air photos, 2005-2012 erosion rates from analysis of repeat aerial LiDAR data, additional ravine monitoring data, and geochemical fingerprinting analyses of suspended sediments.
   - Analyze statistical relationships between channel migration rates, bluff erosion rates, and upland yields with surficial geology, topographic relief, and climate.
   - Utilize sediment budget information to help constrain a sediment delivery model designed to be used with stakeholder groups to make decisions about management options for managing both peak flows and excess fine sediment loading within the watershed.
2. High-resolution bluff erosion monitoring (continuing)
   - Finish analyses of event-scale bluff erosion data
   - Complete comparisons of TLS and aerial LiDAR erosion data on study bluffs in Le Sueur River
   - Work with colleagues on mechanistic model connecting changes in hydrology to bluff erosion rates
3. Channel evolution and paleohydrology (starting fall 2013)
   - Reconstruct effects of past climate change (late Pleistocene, Holocene) on channel geomorphology through field data collection on relict channels preserved on terraces throughout lower Minnesota River basin
   - Reconstruct history of channel incision on Blue Earth and Watonwan Rivers for comparison with valley evolution history for the Le Sueur River (Gran et al., in press).
4. Riparian vegetation effects on modern channel geomorphology (pending)
   - Examine the role of changing timing of peak flows on germination and growth of willow and cottonwood along the lower Minnesota River
   - Determine if changing germination and growth patterns affect overbank deposition rates in lower Minnesota River.

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WSC REACH Progress Report for 2012–2013

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Overview (2012–2013)

Year one of curriculum development for Project REACH resulted in the joined collaboration of six secondary teachers from five school districts in Minnesota, five graduate students, and one faculty member from the University of Minnesota. This progress report will focus on four key aspects of that collaboration: (1) Teacher recruitment, selection, and future collaboration, (2) Professional development and curriculum development located throughout the Minnesota River Basin (MRB), (3) Online spaces for teacher collaboration and public displays of student artifacts, and (4) Socio-scientific research related to curriculum development and classroom implementation.

The professional development (PD) experience was suitably branded as “The River Run: PD with a Splash of Tech” to clearly identify the project’s purpose. The River Run in its initial year (2012-13), has thus far resulted in five days of professional development and curriculum development, with another day planned on August 16, 2013. Subsequent follow-up with teachers and classroom implementation of the developed curriculum will occur in the upcoming 2013-14 school year.

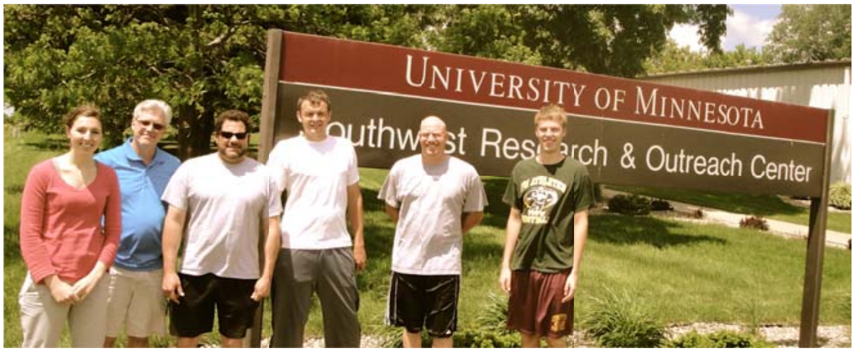
Teachers were introduced to the scientific and socio-scientific components of the MRB, via enriched, experiential learning opportunities with Project REACH scientists and the River Run team. To further provide the opportunity for teachers to develop authentic curriculum addressing the scientific research being conducted in the Minnesota River, a variety of water quality testing technologies were purchased for participating teachers, along with a portable electronic device and laptop computer for data collection and analysis. An online space for collaboration amongst the network of teachers is also in development as teachers and students will be provided an online space in which to contribute media (pictures and video) and information (stories and data) related to the curriculum.

(1) **Teacher Recruitment, Selection, and Continued Collaboration**

The geographic area MRB is large (~300 miles). Therefore, there were a large number of teachers who could have potentially collaborated with the team in its initial year. Efforts were made to contact teachers from the river’s start in western Minnesota to its confluence at the Mississippi River. Email communications were initially sent out to environmental science teachers at the secondary level. Environmental science teachers in Minnesota typically are given more flexibility in the design of their curriculum, and also have a vested interested in frequently getting students outdoors when the opportunity presents itself. State mandated standardized tests and content standards are also not present in environmental science classes. These combined factors, naturally made this group of teachers prime for recruitment.

In total, six teachers (Figure 1) from five secondary schools ultimately agreed to work in collaboration with the River Run team. Teachers from the following cities in Minnesota were involved: Montevideo, Granite Falls, St. Peter, Mankato, and Shakopee. The group exhibited a unified interest in connecting their classrooms via a combined effort and has committed to doing so in the upcoming school year.

Figure 1: Teachers involved in year 1 of the River Run professional development experience.



(2) **Professional Development and Curriculum Development**

Following Clements (2007) *Curriculum Research Framework* to structure the curriculum development and PD, the first of three phases has begun. Thus far, the use of existing research to inform the curriculum development has been applied to the creation of curricular modules. The initial meeting of the group occurred on May 11, 2013 at STEM Education Center in St. Paul, Minnesota. The day was branded as a "Technology Deployment Day" as a total of three new technologies and eight data collection sensors were introduced and utilized. In giving participating teachers these technologies, the collection of localized data, specific to place and time became possible. The educational affordances (Kirschner, Strijbos, Kreijn, and Jelle-Beers, 2004) of such technologies will be utilized to further understand the fundamental principles that define the MRB for teachers and students alike.

Following this initial meeting, four continuous days of PD were planned throughout the MRB, with the experience being based out of the University of Minnesota's Southwest Research and Outreach Center (SWROC) in Lamberton, Minnesota. The decision this facility was chosen can be better understood after reading its mission statement: "*The SWROC and associated properties offer a significant research setting and capacity for long-term agricultural and ecological research on the impacts of conventional, organic and prairie management systems on environmental quality.*" Table 1, provides a glimpse and overview of a majority of the week's events. During the week, the following pieces of data were collected: daily audio journals, daily focus group interviews, and individual interviews. The major revelation of the week's events was the participants' realization of the complex nature of the MRB (scientific and social). This newly found scientific understanding was reiterated numerous times throughout the week in interviews, focus groups, and curriculum development.

Table 1: Professional development experiences for the River Run (June 2013).

Date	Morning	Afternoon
June 10	Southwest Research and Outreach Center: Research and Facility Tour-Jeff Strock, (Ph.D.) Professor, Department of Soil, Water, and Climate: University of Minnesota	Canoe Trip: Minnesota River (Cannon Falls, MN)-Natalie Warren, Wild River Academy
June 11	Canoe Trip: Le Sueur River (Mankato, MN)-Patrick Belmont (Ph.D.) Assistant Professor, Department of Watershed Science: Utah State University	Water Quality and Data Collection Orientation (Mankato, MN)
June 12	Stormwater Management-Shahram Missaghi, Assistant Extension Professor, Department of Water Resources: University of Minnesota	Hydrology 101-Brent Dalzell (Ph.D.) Postdoctoral Research Associate, Department of Soil, Water, and Climate: University of Minnesota Earth System Science (ESS): Curriculum Development Resources
June 13	Socio-Scientific Issues in the Classroom	Curriculum Development: Next Steps and Future Planning

The group of teachers and researchers will again be meeting up on August 16, 2013 in Shakopee, Minnesota to further discuss curriculum implementation and continued collaboration (face-to-face and virtual) for the upcoming 2013-14 school year.

(3) **Online Spaces**

Creating and utilizing an online space for collaboration amongst teachers, students, and researchers is in development. The purpose of the online space is to provide a space for the development of a "community of practice" (CoP) (Barab, Makinster, & Scheckler, 2003). Barab et al. (2003) describe a CoP as "..a persistent, sustained social network of individuals who share and develop an overlapping knowledge base, set of beliefs, values, history and experiences focused on a common practice and/or mutual enterprise" (p. 238). In this context, participating teachers will be developing curriculum focussed on the MRB. The online space, a computer supported collaborative learning (CSCL) environment will be utilized for a variety of purpose. Computer supported collaborative learning environments as described by Kirschner et al. (2004) are "... seen as systems that have interacting parts (i.e., artifacts related to technological, educational, and social affordances) and emergent properties that exceed the sum of the properties of their parts" (p. 47). With the expressed interest in utilizing an CSCL for teachers and students from participating schools in the MRB, a web space (http://projectriverrun.wordpress.com/) that has public and non-public spaces has been created to allow for smoother operations of these interacting parts. The public spaces on the website will include digitally creating artifacts from students at participating schools which will present various sides to the socio-scientific content presented in their classes. The private space will serve as a communication and collaboration hub for all involved to share media, data, and information related to the combined curriculum development effort.

(4) **Socio-scientific Research**

Given the unique characteristics of the MRB and the central hypothesis of the research currently being done on human-amplified natural change (HANC), a research angle from a socio-scientific view has been taken. The inclusion of socio-scientific issues in science curriculum has been called for in the last three decades. Over the last decade, interest in socio-scientific issues (SSI) as research themes and instructional contexts for science education has grown dramatically" (Sadler, 2011, p. 355). Socio-scientific issues serve as a pedagogical strategy which stimulates "individual intellectual development in morality and ethics as well as awareness of the interdependence between science and society" (Zeidler et al., 2005, p. 360).

The work done thus far has resulted in conference proposals for graduate students and faculty from the University of Minnesota at the the following conferences: The Association for Science Teacher Education, The National Association for Research in Science Teaching, and E-Learn: The Association for the Advancement of Computing in Education. Conference proposals revolve around socio-scientific issues and the curriculum implementation process, technology integration in secondary science classroom, and placed-based professional development and its impacts on scientific content knowledge.

Thus far, one graduate student (Engin Karahan: University of Minnesota, STEM Education Doctoral Student) is pursuing his dissertation research with teachers from the River Run. Research conducted thus far includes semi-formal focus group interviews and individual interviews. The research being conducted is aimed at gaining an understanding of teachers' opinions and plans for addressing socio-scientific controversies in teachers' classrooms and will be continued in the 2013-14 academic school year.

Future Research

In 2013-14, research and resources will be focussed around the following areas:

1. **Teacher Continued Collaboration**
    - Continue working with and providing support (educational, scientific, technological, etc.) for the implementation of the developed SSI-focussed curriculum with the current group of teachers.
    - Survey the MRB for potential additions to the current group of secondary environmental science teachers.
2. **Curriculum Development and Classroom Implementation**
    - Continue phase two and three of Clements (2007) *Curriculum Research Framework.*
        - revise curricular modules in accordance with models of children's thinking and learning within the specific content domain
        - conduct formative and summative evaluations in classroom settings
    - Support teachers in collating and organized their developed curriculum for broader audiences.
3. **Collaboration and Collection of Digital Artifacts via the Developed Online Space**
    - Orientate teachers with the technological, social, and educational affordances (Kirschner et al., 2004) of the online space.
    - Facilitate the development of a Community of Practice (CoP) (Barab et al., 2003) with the current teacher group by providing updated, relevant content in which teachers can utilize in their own classrooms while discussing asynchronously online.
    - Collect and display, student-created digital media related to the socio-scientific issues explored within the MRB for the public.
4. **Socio-scientific and Technology Integration Educational Research**
    - Perform classroom observations and collect data (classroom artifacts, student interviews, etc.) related to the implemented curriculum.

- Investigate the integration of technology by teachers in selected classrooms to reveal teachers technological pedagogical content knowledge (TPACK) (Mishra and Koehler, 2006).

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