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Special Section:
Dynamics in Intensively Managed Landscapes: Water, Sediment, Nutrient, Carbon, and Ecohydrology

Key Points:
- Observatory-scale study of MN River Basin created integrative data sets and reduced complexity models to understand environmental change
- Data sets include water biogeochemistry, sediment sources and sinks, sediment fingerprinting, geomorphic change detection, and bathymetry
- Modeling efforts focus on basin-scale environmental transport to inform land management, reduce pollutant export, and improve river biota

Supporting Information:
- Supporting Information S1

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The Power of Environmental Observatories for Advancing Multidisciplinary Research, Outreach, and Decision Support: The Case of the Minnesota River Basin

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Abstract Observatory-scale data collection efforts allow unprecedented opportunities for integrative, multidisciplinary investigations in large, complex watersheds, which can affect management decisions and policy. Through the National Science Foundation-funded REACH (REsilience under Accelerated CHange) project, in collaboration with the Intensively Managed Landscapes-Critical Zone Observatory, we have collected a series of multidisciplinary data sets throughout the Minnesota River Basin in south-central Minnesota, USA, a 43,400-km^2 tributary to the Upper Mississippi River. Postglacial incision within the Minnesota River valley created an erosional landscape highly responsive to hydrologic change, allowing for transdisciplinary research into the complex cascade of environmental changes that occur due to hydrology and land use alterations from intensive agricultural management and climate change. Data sets collected include water chemistry and biogeochemical data, geochemical fingerprinting of major sediment sources, high-resolution monitoring of river bluff erosion, and repeat channel cross-sectional and bathymetry data following major floods. The data collection efforts led to development of a series of integrative reduced complexity models that provide deeper insight into how water, sediment, and nutrients route and transform through a large channel network and respond to change. These models represent the culmination of efforts to integrate interdisciplinary data sets and science to gain new insights into watershed-scale processes in order to advance management and decision making. The purpose of this paper is to present a synthesis of the data sets and models, disseminate them to the community for further research, and identify mechanisms used to expand the temporal and spatial extent of short-term observatory-scale data collection efforts.

1. Introduction

Intensively managed agricultural landscapes can have profound effects on the water quality and ecological integrity of downstream receiving waters (e.g., Rabalais et al., 1996; Tilman et al., 2001; Wood & Armitage, 1997). Data on water quality, discharge, precipitation, and land use are often available from national, state, and local agencies charged with regulating and protecting water resources; however, understanding and modeling the complex effects of land use and hydrologic change on geomorphology, sediment transport, nutrient flux, and ecosystem response requires additional multidisciplinary data collection. Opportunities to collect all of these data sets in a single large watershed are rare, but investments in observatory-scale

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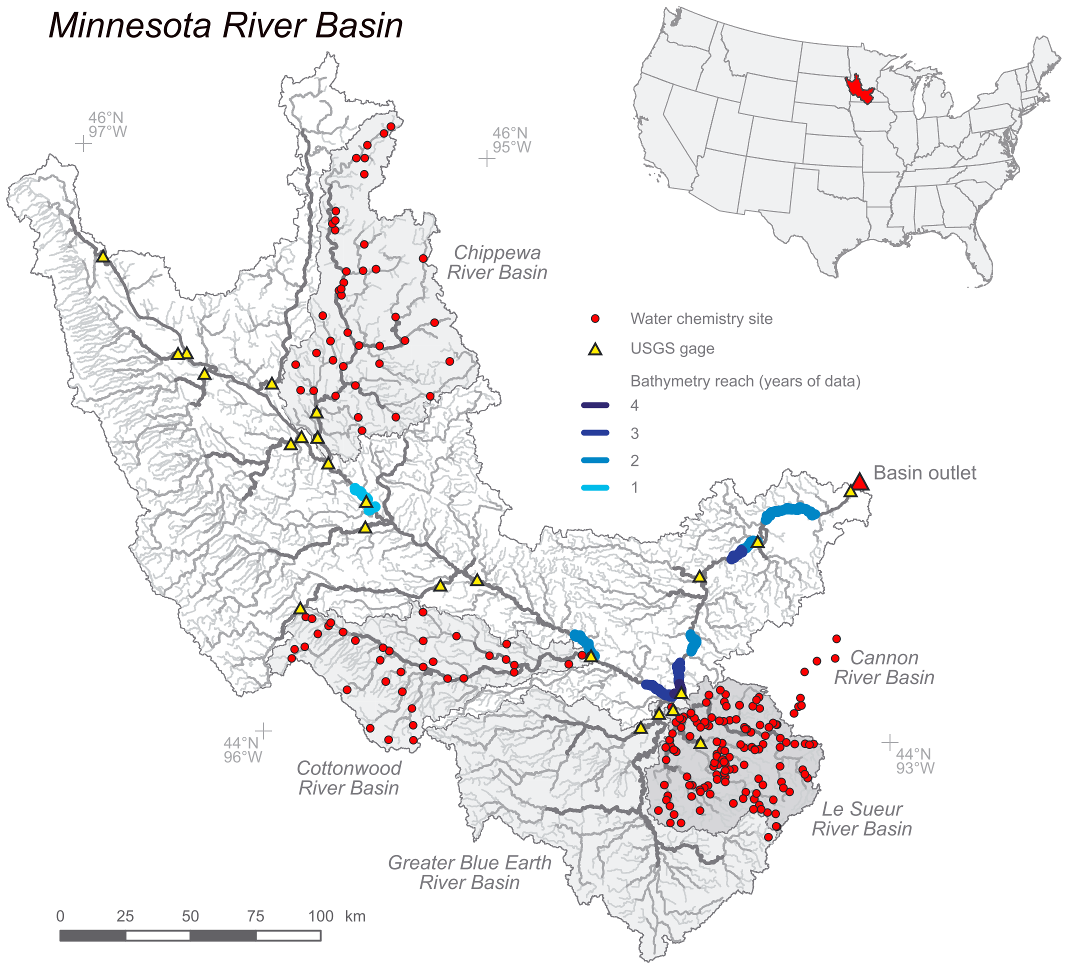

Figure 1. Data collection sites within the Minnesota River Basin (MRB), including water chemistry sites (Dolph, Hansen, Kemmitt, et al., 2017) and river bathymetry data collection (Kelly et al., 2018). Inset shows location of the MRB within the continental United States. A few water chemistry sites were located in the Cannon River Basin to the east of the MRB. Additional state agency monitoring sites are not shown here (see Table S1 for details). USGS = U.S. Geological Survey.

data collection efforts are now providing opportunities for integrated research in diverse landscapes throughout the United States. Through the National Science Foundation (NSF)-funded REACH (REsilience under Accelerated CHange) project as part of the Water Sustainability and Climate initiative, and in collaboration with the NSF-funded Intensively Managed Landscapes-Critical Zone Observatory (IML-CZO), we have undertaken a strategic campaign to collect a series of detailed, multiprocess, multidisciplinary data sets throughout the Minnesota River Basin (MRB) in south-central Minnesota, USA. Within the MRB, an intensive focus was placed on the Le Sueur River Basin, a key subwatershed that contributes a disproportionately large amount of sediment and nutrients to the Minnesota River (Figure 1; Belmont et al., 2011; Gran et al., 2009; Musser et al., 2009). These targeted data sets were integrated into stream gage and precipitation monitoring networks run by state and federal agencies so that the longer-term hydrologic data could provide a richer context for the shorter-term data collection efforts described here. Collectively, these data sets allow for the exploration of interactions and feedbacks between hydrologic and land use change and the geomorphic, geochemical, and biophysical responses in a large intensively managed agricultural basin. Much of this work was done in collaboration with local stakeholders including local, state, and federal resource managers, agricultural interest groups, land owners, scientists, and nonprofits and reflects an intentional, iterative, and participatory process in data collection and model building (Cho et al., 2019; Cho, 2017). In addition, our data collection and modeling efforts were explicitly integrated with the development of educational materials for teachers and high school students in the region, to broaden student participation in scientific inquiry motivated by challenges facing the natural world in their home landscapes.

Hydrologic changes within a watershed can lead to a complex response in the channels and channel networks with potential negative repercussions on erosion, transport of sediment and pollutants, and ecosystem integrity (e.g., Blann et al., 2009; Konar et al., 2013; Schilling et al., 2008; Vörösmarty & Sahagian, 2000). The MRB is particularly sensitive to hydrologic change, with deeply incised tributaries eliciting a strong geomorphic response to ongoing changes in hydrology (Belmont et al., 2011; Belmont & Foufoula-Georgiou, 2017; Call et al., 2017; Foufoula-Georgiou et al., 2015; Gran et al., 2013; Kelly et al., 2017). This makes it a valuable location to systematically investigate linkages between changes in the landscape and river ecohydrologic and morphologic response. Here, we describe the geomorphic, geochemical, and biophysical data sets collected under the auspices of REACH, give examples of analyses and modeling approaches made possible through this collective effort, and include links to curricular materials that focus on understanding water, sediment, and nutrient transport in IML. All of the data sets and modeling approaches presented here are now publicly available. The goal of this paper is to present an integrated synthesis of these data sets and models, both as an example of how interdisciplinary science can inform key scientific and societal questions and to encourage additional research into IML as a prototype of coupled human-natural systems undergoing change (Kumar et al., 2018). This data collection and analysis effort differs from some of the longer-term observatory-scale efforts (e.g., Goodman et al., 2015; Hobbie et al., 2003; Utz et al., 2013; White et al., 2015; Wilson et al., 2018) but provides an example of how leveraged publicly available data and previous studies can be optimally integrated to maximize science. Specifically, we demonstrate how targeted collection of biogeochemical data and repeat geomorphic data coupled with routine stream gage, meteorological, topography, and land use data can be used to make transdisciplinary advances in our understanding of how sediment, water, and nutrients move through and transform in IML.

2. MRB Environmental Observatory

The MRB drains approximately 43,400 km^2 of south-central Minnesota, South Dakota, and Iowa, USA (Figure 1). The Minnesota River itself is disproportionately small (~100 m wide; Lauer et al., 2017) compared to its wide valley (up to 2 km wide; Lenhart et al., 2013) carved by outflows from glacial Lake Agassiz near the end of the last glaciation (Clayton & Moran, 1982; Matsch, 1983). Incision on the mainstem Minnesota River created knickpoints that have propagated upstream on all major tributaries, leading to deeply incised lower tributary valleys in an otherwise relatively flat postglacial landscape (Belmont, 2011; Gran et al., 2009, 2013).

The MRB is an optimal setting for understanding the complex cascade of changes that occur due to land use and hydrologic alterations from intensive agricultural management and ongoing climate change. There are three main reasons for this: (1) Large-scale conversion of prairie to primarily row-crop agriculture with accompanying changes in surface and subsurface drainage has left the MRB strongly altered from its pre-European settlement state, affecting its connectivity and hydrologic response (Figures 2a and 2b; Foufoula-Georgiou et al., 2015; Lenhart et al., 2012; Schottler et al., 2014). Analyses of available discharge, precipitation, and land use/land cover data have demonstrated increasing flows over time on the mainstem Minnesota River and its tributaries (Foufoula-Georgiou et al., 2015; Kelly et al., 2017; Novotny & Stefan, 2007); (2) The deeply incised postglacial valleys are particularly sensitive to changes in hydrology, and the strong geomorphic response in channels has important ramifications for erosion and sediment loading (Belmont et al., 2011; Cho, 2017; Gran et al., 2013; Kelly & Belmont, 2018; Lauer et al., 2017; Lenhart et al., 2018; Vaughan et al., 2017); and (3) Dramatic increases in fertilizer input, coupled with the drainage of ~80% of historic wetlands in the region since European settlement, have contributed to high loads of nitrogen and phosphorus throughout the watershed creating numerous local and downstream water quality challenges, including drinking water contamination, algal blooms, hypoxic zones, and harm to aquatic life (Boardman, 2016; Hansen et al., 2018; USACE, U.S. Army Corps of Engineers St. Paul District, M, 2004).

Within the MRB, we focus particular effort on the 9,200-km^2 Greater Blue Earth River Basin (GBERB), which includes the Le Sueur, Blue Earth, and Watonwan Rivers (Figure 1). The GBERB and the Le Sueur River, in particular, contribute a disproportionately large amount of sediment, nitrogen, and phosphorus to the mainstem Minnesota River (Belmont et al., 2011; Musser et al., 2009). The 2,800-km^2 Le Sueur River Basin has been the focus of a decade-long sustained effort to understand the role of geomorphic

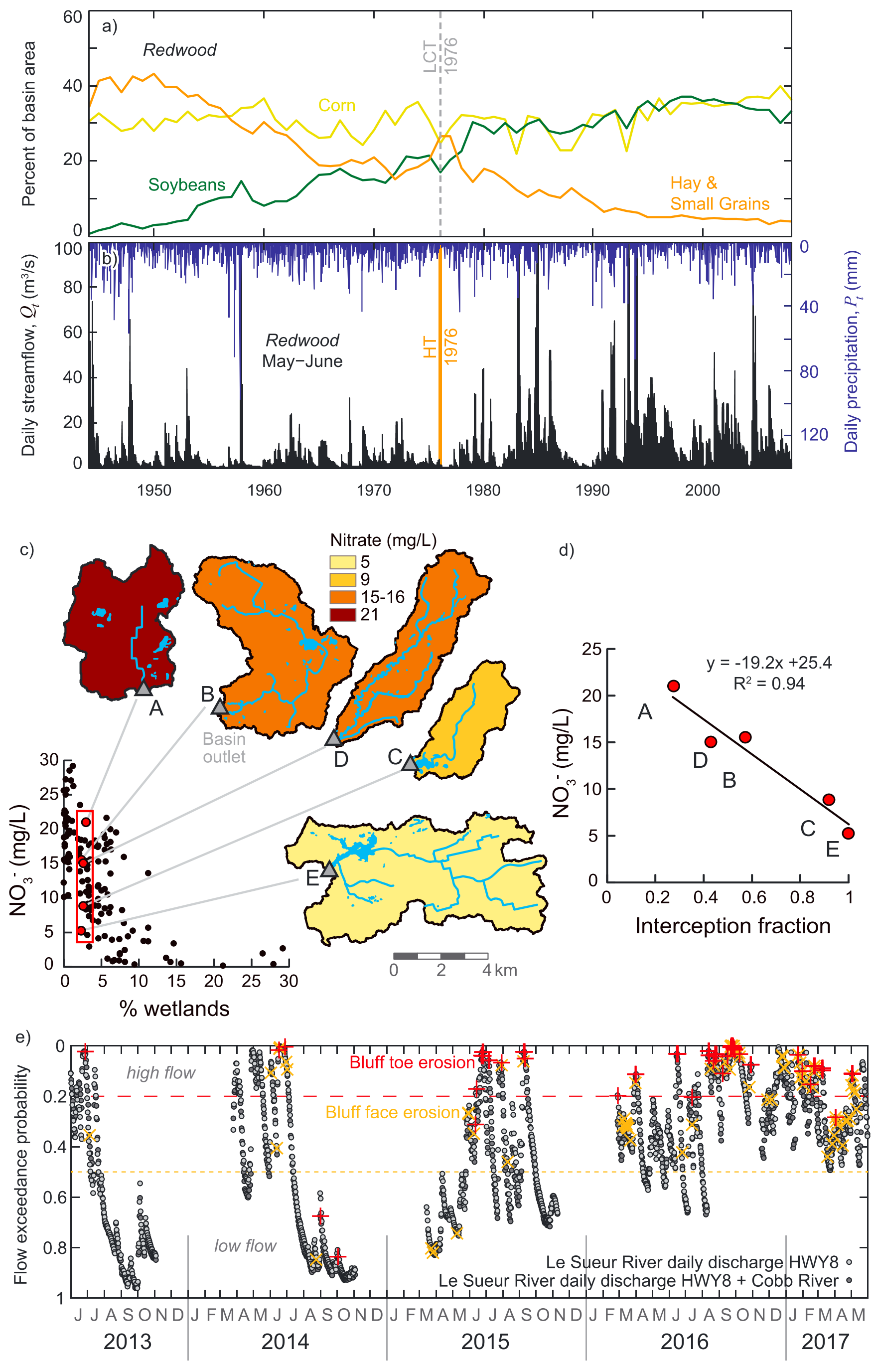

Figure 2. Examples of key project findings based on analysis of publicly available data combined with original field data sets for water quantity and quality (e.g., nitrate, sediment, and phosphorus). (a, b) The imprint of agricultural land use change on hydrologic change. Using daily streamflow data in the growing season of May–June to minimize climatic effects, the hydrologic transition (HT) is observed coincident with the conversion to soybeans, that is, following the land-cover transition (LCT), which as objectively extracted from land-cover data for the Redwood River, a tributary to the Minnesota River. Modified from Foufoula-Georgiou et al. (2015). (c) Effect of wetland spatial patterning on riverine nitrate. Five sites with similar crop cover (69–84% in increasing order B-E-D-A-C) and 2.32–2.97% nonephemeral wetlands showed different nitrate concentrations. (d) Accounting for spatial wetland patterning (parameterized as the percentage of intercepted area = fraction of a site's watershed area intercepted by a wetland) significantly reduced variability. Nitrate observations at A–C were measured in 2015 and D and E in 2014. Modified from Hansen et al. (2018). (e) Timing and flow conditions for bluff toe and bluff face erosion as documented via daily time lapse photography on 10 bluffs in the lower Le Sueur River. Mean daily discharge values are plotted in terms of flow exceedance from two gages (32076001 and 32071001) in the Le Sueur River showing flows under which erosion dominantly occurs. Modified from Kelly and Belmont (2018).

history and structure on sediment loading (Belmont et al., 2011; Day et al., 2013a, 2013b; Gran et al., 2011, 2009, 2013). The data collected in the Le Sueur prior to the REACH effort, as part of the National Center for Earth Surface Dynamics, an NSF Science and Technology Center, laid a strong foundation upon which we were able to expand both spatially (throughout the entire MRB) and across multiple disciplines.

The goal of our interdisciplinary collaboration was to investigate the hypothesis that specific places, times, and processes have disproportionate impacts on the ways that human changes to intensively managed agricultural landscapes propagate through river networks resulting in downstream water quality impacts (Belmont & Foufoula-Georgiou, 2017). This goal necessitated the compilation, integration, and synthesis of large, existing public data sets (Table S1 in the supporting information) as well as the generation of large, unprecedented original field data sets as described below. The value of the publicly available hydrology, topography, water quality, imagery, and land cover data sets cannot be overstated and gave the additional data sets here a rich temporal, spatial, and historical context. Many of the data sets were critical in the development of a series of reduced complexity models designed to understand key processes and linkages between processes at the watershed scale (Call et al., 2017; Cho, 2017; Cho et al., 2017; Czuba et al., 2017; Czuba & Foufoula-Georgiou, 2014, 2015; Hansen, Czuba, et al., 2016), while additional efforts focused on integrating new knowledge into existing mechanistic modeling frameworks like the Soil and Water Assessment Tool (e.g., Kumarasamy & Belmont, 2018; Mitchell et al., 2018).

3. New Interdisciplinary Data Sets for Watershed-Scale Studies in IML

New data sets were collected throughout the MRB, including the Cottonwood, Chippewa, and GBERBs and along the mainstem Minnesota River. In addition, many public data sets were utilized and synthesized to provide context for the interpretation of the new data sets collected here (Table S1). The data sets collected throughout the MRB are described below, together with the science questions that motivated their collection and examples of the analyses they enabled to test hypotheses and develop new models.

3.1. Watershed-Wide Water Chemistry and Biogeochemical Data

Detailed water chemistry data are needed to inform our understanding of how processes like denitrification, assimilation, and phosphorus sorption-desorption affect the movement of water quality constituents through river networks. Prior to the onset of this project, these data were limited for our study region, especially at the subwatershed scale. We addressed this need with an extensive field campaign that spanned four field seasons from 2013–2016. Biogeochemical data were collected under multiple flow conditions from more than 200 ditch, stream, and river sites across the MRB (Figure 1). Data collected include (1) water chemistry (total dissolved nitrogen [N], nitrate-N, nitrite-N, ammonium-N, particulate N, soluble reactive phosphorus, total dissolved phosphorus, particulate phosphorus, total phosphorus, dissolved organic carbon, dissolved inorganic carbon, particulate carbon, chlorophyll a, total suspended solids, volatile suspended solids, δ^{2}H and δ^{18}O stable isotopes of site water, specific ultraviolet absorbance of site water, and fluorescence index of site water); (2) stable isotopes (δ^{13}C, δ^{15}N, and δ^{2}H) of invertebrate consumers, particulate carbon, and potential food sources; (3) denitrification rates and characteristics of benthic sediment in agricultural drainage ditches; (4) phosphorus characteristics including total and extractable dissolved phosphorus and phosphorus sorptive properties of sediment from agricultural uplands, bluffs, ditchbanks, streambanks, and ravines; and (5) stream discharge. The data sets, as well as methods for data collection and quality control, are described in more detail in Dolph, Hansen, Kemmitt, et al. (2017) and Baker (2018).

The wide spatial and temporal coverage of these data sets enabled testing of novel hypotheses about the watershed-scale influences of wetlands on downstream nitrate concentrations (i.e., Figures 2c and 2d) under different flow conditions (Hansen, Dolph, & Finlay, 2016; Hansen et al., 2018) with results contrasting from other empirical watershed-scale studies in part because of the wide variation in wetland and shallow lake cover in the MRB (Hansen et al., 2018; Strayer et al., 2003). The data sets were used in the development of a process-based river network framework for predicting nitrate and dissolved organic carbon concentrations as a function of the location and specific attributes of wetlands (Czuba et al., 2018). The data set also allowed for quantification of multiple varied biophysical processes important to nutrient spiraling and transport in streams and rivers of our study region, including phosphorus sorption-desorption and the role of sediment on modulating phosphorus form and bioavailability (Baker, 2018), and algal assimilation (Dolph, Hansen & Finlay, 2017). Integrating the findings of these investigations of biophysical processes into frameworks such as watershed sediment budgets (section 3.2) and reduced complexity models (section 4) has also allowed for the quantification of the role of these processes in watershed-scale export of nutrients. Many of these processes are complex, and have heretofore been poorly characterized in river systems (Alexander et al., 2009; Bernot et al., 2006; Seitzinger et al., 2006). Greater understanding of these biophysical processes informed by extensive data collection in the field has enabled an ongoing interdisciplinary effort by members of our group to optimize conservation scenarios on the landscape for simultaneous mitigation of multiple water quality pollutant endpoints. Beyond its current uses, the biogeochemical data set could be applied to many possible future investigations, including the role of wetlands in modifying watershed-scale phosphorus export, food web dynamics in agricultural streams, and modeling efforts aimed at emerging contaminants that may be affected by stream and river water chemistry.

3.2. Geomorphic Data on Sediment Sources, Erosion Rates, and Erosional Mechanisms

Excess fine sediment is one of the largest contributors to water quality problems (Bilotta & Brazier, 2008; Wood & Armitage, 1997), increasing turbidity and often leading to additional pollution of sediment-bound nutrients like phosphorus (Correll, 1998). Yet targeted management of fine sediment loads can only be accomplished with an understanding of where sediment is derived from within a watershed and what conditions lead to enhanced erosion. To better understand how sediment sources and sinks are distributed across the MRB and how they respond to external forcings such as altered hydrology due to climate and landscape change, geomorphic data were collected both in the field and using remotely sensed data. Data on sediment sources and sinks were collected at the watershed scale, while detailed reach-scale analyses focused on channel and riparian corridor response to flows, with several major flooding events captured in time series data. Most of the geomorphic data were collected in the GBERB (Figure 1). Many of these data sets from the Le Sueur River Basin began prior to the REACH project and have been built upon and expanded as part of the REACH effort. In addition to the data sets themselves, many automated mapping tools were developed that could be used in other basins to extract features like channel networks and terraces from high-resolution lidar data (e.g., Passalacqua et al., 2015; Stout & Belmont, 2014).

Within the GBERB, source delineation, change detection, and erosion rate data were used as the foundation of an integrated sediment budget (Belmont et al., 2011; Bevis, 2015; Gran et al., 2011). Major sediment sources (banks, bluffs, ravines, and uplands) and sinks (floodplains and lakes) were delineated from high-resolution (1–3 m) lidar data available throughout the state of Minnesota (Mn.IT Services, 2018; Figure 3). ArcGIS shapefiles of source and sink delineations including ravines, bluffs, channel centerlines (in 1938 and 2008), and lakeshed and watershed boundaries in the GBERB are available in Bevis and Gran (2017) with full descriptions of mapping methods in the metadata and Bevis (2015). Rates of erosion were determined through a variety of methods including change detection analyses of lidar and georeferenced historical air photos along channel corridors (Belmont et al., 2011; Day et al., 2013b; Lauer et al., 2017; Passalacqua et al., 2012), repeat aerial and terrestrial lidar on river bluffs (Day et al., 2013b, 2013a; Schaffrath et al., 2015), repeat structure-from-motion (SfM) photogrammetry and time-lapse photography of river bluffs (Kelly & Belmont, 2018), and autosampler monitoring of ravines (Belmont et al., 2011; Gran et al., 2011). Sediment fingerprinting (described below) provided an independent constraint on sediment partitioning. The integrated sediment budget formed the foundation for investigations into landscape evolution in incising basins (Belmont, 2011; Gran et al., 2013); reduced complexity sediment routing and delivery models (Cho et al., 2019; Cho, 2017; Czuba et al., 2017; Gran & Czuba, 2017; Viparelli et al., 2013); investigation of the contribution of sediment sources to a watershed-scale phosphorus budget (Baker, 2018); and participatory modeling efforts with stakeholders to determine optimal combinations of hydrology, field, and near-channel management options to cost-effectively reduce sediment loading in the GBERB (Cho et al., 2019; Cho, 2017; Cho et al., 2017; Lang & Rabotyagov, 2018).

Each of the methods of change detection detailed above relies upon measuring change over a discrete window of time, ranging from 70 years for air photo comparisons to 6–12 months for repeat terrestrial lidar data. While high-resolution topographic data have greatly enhanced our ability to identify landscape features over spatially extensive areas (Passalacqua et al., 2015), few data sets have documented geomorphic change with high resolution in both time and space. Kelly and Belmont (2018) used a combination of SfM and time-lapse photography to document erosion of 20 large bluffs on daily and seasonal timescales over three years in the GBERB (i.e., Figure 2e). SfM surveys document extreme erosion at two of the monitored sites on a seasonal

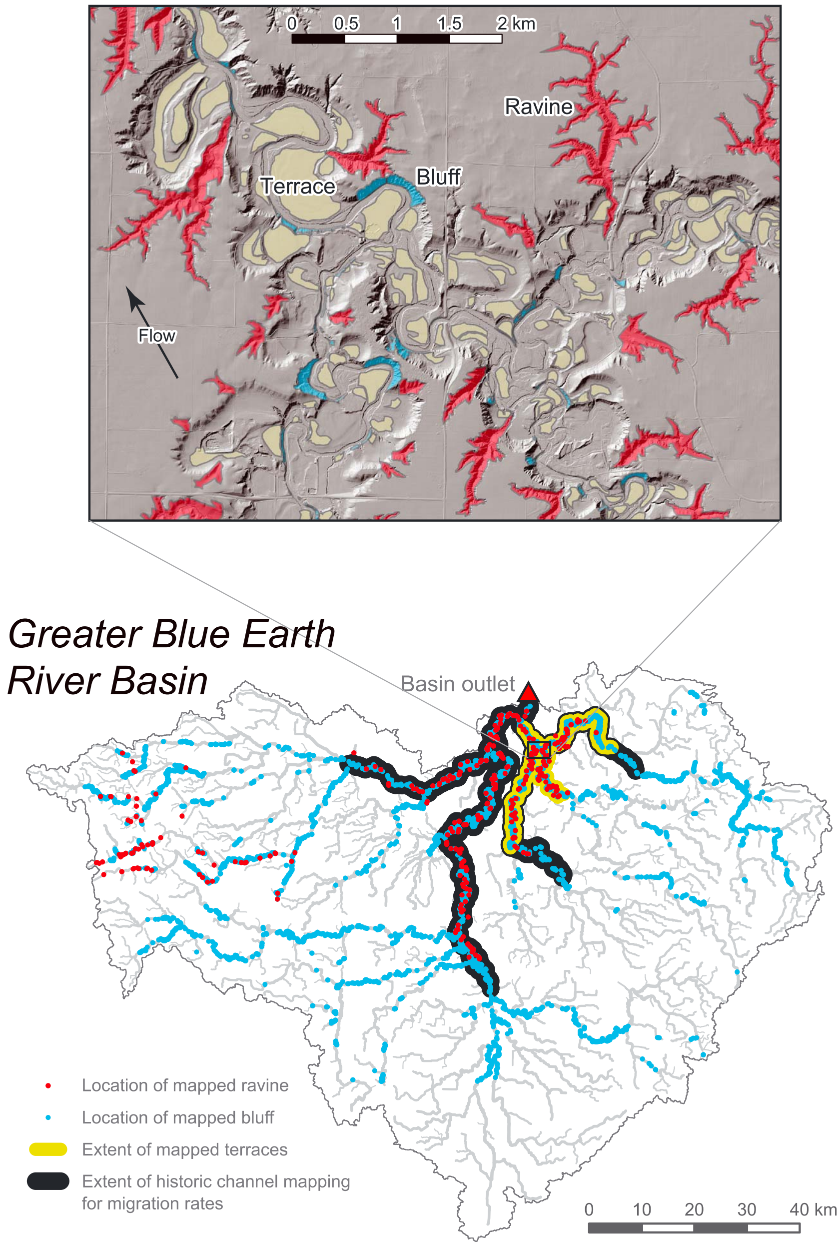

Figure 3. The Greater Blue Earth River Basin and additional geomorphic data collection locations spanning this basin scale. See Figure 1 for location of Greater Blue Earth River Basin within the Minnesota River Basin. Inset shows the detailed mapping of ravines, bluffs, and terraces from the underlying lidar data (Bevis & Gran, 2017; Stout & Belmont, 2014).

timescale and time-lapse photos document extensive erosion at an additional 18 sites at a daily time step. The raw data and derivative products are available in Belmont (2018b).

3.3. Reach-Scale Channel Cross-Sectional Data Before and After Major Flood Events

The MRB has experienced increasing flows over the past few decades (Kelly et al., 2017; Novotny & Stefan, 2007; Schottler et al., 2014) as well as changes in the hydrologic response, such as altered hydrograph shapes (Foufoula-Georgiou et al., 2015) and reduced water residence times (Danesh-Yazdi et al., 2016). River channels naturally increase in width and depth to accommodate such increases in flow, but the partitioning between width and depth increases is not well known (Lane et al., 2007; Slater et al., 2015). Using field surveys, we documented the effects of several large floods in MRB tributaries for which we had previously surveyed 44 river cross sections spanning two very distinct geomorphic zones: (1) low-gradient, passively meandering reaches in the upstream portions of the rivers, and (2) actively meandering and downcutting rivers in the knickzone farther downstream. Specifically, repeat cross-section surveys were conducted using a high-precision real-time kinematic GPS system (rtkGPS) or engineer's level and stadia rod on the Le Sueur and Maple rivers during 2008 and 2015. The flood of record (going back to 1940) occurred in 2010, with a peak magnitude at the mouth of the Le Sueur River (U.S. Geological Survey gage 05320500) of 863 m^3/s nearly 170 m^3/s larger than the previous flood of record in 1965. Additional large floods occurred in 2011 (402 m^3/s), 2013 (294 m^3/s), and 2014 (442 m^3/s). Call et al. (2017) found that the observed increases in channel dimensions were significant, but they represent only a small fraction of the changes needed to reach equilibrium under these higher flow conditions. Call et al. (2017) used these data to develop a reduced complexity model of changes in channel width, depth, and slope in response to systematic shifts in flood regime and sediment supply and explore the implications for floodplain inundation. Model results highlight the importance of channel adjustment capacity and changes in variance of flood flows in predicting floodplain inundation. The model scripts and data are available through Belmont (2018a).

3.4. Sediment Fingerprinting Data to Discern Terrestrial Versus River Network Sediment Sources

Sediment fingerprinting is a novel approach for sediment source apportionment that is entirely independent of other modeling, remote sensing, or field measurement techniques (Belmont et al., 2014; A. Collins & Walling, 2002; Gellis & Walling, 2011; Koiter et al., 2013; Smith & Blake, 2014; Walling & Woodward, 1992). Assuming geochemical properties can be identified to discriminate among various sources, sediment fingerprinting provides information regarding spatially integrated sediment loading from different sources throughout the watershed upstream from the sample location and is temporally discrete according to the time the sample was collected. We used sediment fingerprinting as an independent check on the sediment budget described above in section 3.2 (Belmont et al., 2011; Bevis, 2015) as well as to determine sediment apportionment in specific flow events.

We collected, analyzed, and compiled 143 sediment fingerprinting samples from source areas and suspended sediment in the GBERB. Samples were analyzed for meteoric beryllium-10 (^{10}Be), excess lead-210 (^{210}Pb), and cesium-137 (^{137}Cs). These specific tracers were selected because they have significantly disparate half-lives. Generally, sediment derived from upland agricultural soils is rich in all three tracers. Sediment derived from actively eroding bluffs is devoid of all three tracers. However, sediment that is temporarily deposited in floodplains and subsequently remobilized by bank erosion is enriched in meteoric ^{10}Be but deficient in ^{210}Pb and ^{137}Cs after 75–100 years in storage. Thus, the relative amounts of conservative ^{10}Be to the other two nonconservative tracers provides insights regarding the fraction of sediment derived from uplands versus bluffs and streambanks. The unmixing model presented by Belmont et al. (2014) was used to compute the proportion of sediment from each source area. Lauer et al. (2016) and Viparelli et al. (2013) used a portion of the sediment fingerprinting data to develop a geochemically tagged sediment routing model that accounts for production and decay of radioisotopes in the floodplain. The data are available through Belmont (2018b).

Sediment fingerprinting data provided some pivotal and surprising results that could not have been obtained by any other means. Specifically, they confirmed a temporal shift in sediment sources from primarily bluffs and near-channel sediment sources prior to Euro-American settlement, to dominantly agricultural fields in the upper, low relief portions of the GBERB throughout the midtwentieth century, and most recently a shift back to dominantly near-channel bluff and bank sediment derived from the lower, higher relief knickzone portions of the GBERB over the last century (Belmont et al., 2011). This finding has been pivotal in informing the design of new quantitative approaches to account for the importance of near-channel sediment to total sediment yields exported from intensively managed agricultural landscapes in the MRB (Cho et al., 2017).

3.5. Bathymetry Mapping of the Minnesota River to Link Morphology and Dynamics

River channel beds can be highly dynamic over time; thus, repeat mapping of river bathymetry is essential for quantifying aquatic habitat, simulating hydraulics, and monitoring change in river morphology over time. Yet bathymetric maps of rivers remain somewhat rare, largely due to logistical challenges in data collection. Building on top of the flurry of research activities, we leveraged funding from the Minnesota Department of Natural Resources to map extensive areas of the Minnesota River channel bed. Between 2013 and 2016, we mapped a total of 220 km of the mainstem Minnesota River using an RD Instruments River Ray Acoustic Doppler Current Profiler coupled with an rtkGPS system. Most reaches were mapped repeatedly (two to four times) to track changes over time (Figure 1). We identified systematic changes in channel and bar morphology and documented a surprising amount of channel change, with pools scouring and filling by as much as 7 m locally over 2 years (Kelly et al., 2018). The raw data sets, derivative products, and Python postprocessing scripts are all available via NSF Datanet Hydroshare (Kelly et al., 2018) and will be useful to answer a wide variety of basic and applied science and engineering questions ranging from improvements in our basic process understanding of meander migration and sediment transport to engineering applications such as where to install structures to manage invasive carp. Additional details on data collection and validation are available as part of the metadata (Kelly et al., 2018).

4. Reduced Complexity Modeling

The multidisciplinary data collection efforts described above allowed development of a series of integrative reduced complexity models that provide deeper insight into how water, sediment, and nutrients move and transform through a large channel network. Many of these modeling efforts represent the culmination of efforts to merge interdisciplinary data sets detailed above to gain new insights into watershed-scale processes. As channel network structure impacts the distribution and structure of ecosystem processes and functions (Benda et al., 2004; Campbell Grant et al., 2007; Carrara et al., 2012), these models allow exploration of critical hot spots where fluxes accumulate or transform (Czuba et al., 2018; Czuba & Foufoula-Georgiou, 2015) and help provide insight into ecosystem processes in heterogeneous dendritic networks in IML (McCluney et al., 2014). We describe four examples to highlight the wide range of scientific questions that can be addressed with data-driven models, from bedload transport in networks to mussel population dynamics, and to enable other researchers to find all of the different models that were guided and validated by the collected data sets.

4.1. Bed-Material Network-Routing Model

The design of conservation scenarios effective over longer-term periods is contingent on understanding where and when pollutants are mobilized. In particular, identification of vulnerable areas/times of landscape response to hydrology can aid in understanding how climatic trends and management decisions may unexpectedly alter downstream pollutant loads. To understand how complex spatial and temporal factors regulate sediment delivery in the MRB, a network-based bed-material routing model was developed by Czuba and Foufoula-Georgiou (2014). The framework identified synchronization and amplification of sediment delivery from specific places in the basin, an emergent phenomenon with consequences for predicting and managing future sediment loads. Czuba and Foufoula-Georgiou (2015) built upon this framework to identify hot spots of geomorphic change by developing a cluster persistence index, which evaluated how much and for how long individual sediment inputs persisted within links of the river network. Reaches with high cluster persistence indices aligned well with reaches that had high rates of channel migration, as mapped from repeat air photos for the sediment budget detailed above in section 3.2 (Belmont et al., 2011; Bevis, 2015; Bevis & Gran, 2017).

The sediment budget for the Greater Blue Earth River was then used to inform realistic temporally recurrent, spatially variable sediment inputs to the model by Czuba et al. (2017). This model breaks away from traditional Eulerian sediment transport models and instead takes a Lagrangian approach focused on process-based time delays of sediment transport through a river network. By condensing much of the underlying dynamics into a time delay, the model became simple enough to extend throughout an entire river network at watershed scales. In addition, in-channel storage dynamics were incorporated where an excess of sediment entered in-channel storage, adjusted channel slope, and thereby affected sediment transport. One key finding was that low transport capacity reaches acted as upstream controls on downstream sediment transport; that is, these reaches acted as sediment bottlenecks in the river network. Gran and Czuba (2017) used the underlying model of Czuba et al. (2017) to investigate the role of river network structure in the evolution of sediment pulses. They found that the spatial pattern of relative transport capacity exerted a strong control on whether sediment pulses transported downstream or dispersed from a fixed location.

These model codes are all available from CSDMS (Community Surface Dynamics Modeling System; Czuba, 2018b). They allow the user to analyze bed-material sediment dynamics in river networks under varying levels of complexity depending on the availability/knowledge of input data.

4.2. Nitrate Network-Routing Model

As water routes through a wetland-river network, nitrogen in the form of nitrate can be removed from the system via denitrification, modulated by the balance in nitrate versus organic carbon availability and residence time (Alexander et al., 2009; Fisher & Acreman, 2004; Groffman et al., 1996; Kadlec, 2012; Lowrance et al., 1995, 1984; Seitzinger et al., 2006). To better capture how nitrate moves through a river network, a model was created with an integrated wetland-river network to quantify nitrate-nitrogen and organic carbon concentrations in order to estimate overall nitrate export (Czuba et al., 2018). By explicitly incorporating the location and size of wetlands throughout the network as well as multiple competing limitations on nitrate removal, the model captures hierarchical effects and spatial interactions associated with nitrate transformations and removal. The model was applied to the Le Sueur basin, calibrated and validated using synoptic field measurements described in section 3.1 above (Dolph, Hansen, & Finlay, 2017; Dolph, Hansen, Kemmitt, et al., 2017; Hansen, Dolph, & Finlay, 2016), and assessed using a sensitivity analysis of model results to uncertain parameters. This model showed that as nitrate concentration, organic carbon availability, and residence time changed through the network and with varying discharge, it impacted the overall limits to nitrate removal rate via denitrification. The key finding of the model was that increasing water residence time (via slowing the flow) was the most effective mechanism for reducing watershed-scale nitrate concentrations and downstream loads in the Le Sueur basin. Residence time was even more limiting than organic carbon concentrations (which may limit denitrification process rates). This framework can help with assessing where and how to restore wetlands to reduce nitrate loads from agricultural watersheds. Model code is available through CSDMS (Czuba, 2018a). An interactive, online computer-simulation version of the model was also developed for use in high school environmental science classrooms (more on curriculum in section 5 below) and can be found at http://maps.umn.edu/le-sueur-nitrates/ (last accessed 22 September 18).

4.3. Management Options Simulation Model

Participatory modeling has been shown to be an effective method for developing a consensus approach to solve environmental problems (Falconi & Palmer, 2017). However, participatory modeling efforts require nimble models that run quickly, allowing for real-time feedback in stakeholder meetings. To accomplish this, the Management Option Simulation Model (MOSM) was developed with extensive stakeholder input and feedback in the GBERB to identify the most cost-effective suite of management options to reduce fine sediment loading to the Minnesota River (Cho et al., 2019; Cho et al., 2017). MOSM simulates water and sediment routing across the watershed and incorporates different styles of management options that either reduce erosion of field and near-channel sediment sources or reduce sediment delivery to streams. It utilizes the innovative Topofilter model (Cho et al., 2018) to simulate spatially variable sediment delivery ratios for field and stream components, and the detailed sediment budget described in section 3.2 to provide near-channel sediment inputs. MOSM was later coupled with an additional component that tracked development of waterfowl habitat allowing one to compare cost-benefit tradeoffs for competing objectives (i.e., sediment reduction vs. waterfowl habitat). MOSM is available from the University of Minnesota Digital Conservancy (Cho et al., 2017), with the waterfowl optimization extension model available through the Open Source Framework (Lang & Rabotyagov, 2018).

4.4. RiverMUSE Model

Mussel populations respond to variations in suspended sediment concentrations that can occur from changes in land use or climate. Under the hypothesis that high suspended sediment concentrations are detrimental to mussel growth and reproduction, the process-driven River MUssel-SEdiment Interaction (RiverMUSE) model was created to simulate mussel population dynamics as an interaction between changes in streamflow, phytoplankton (food) availability, and suspended sediment concentration (Foufoula-Georgiou et al., 2015; Hansen, Czuba, et al., 2016). After calibrating and validating RiverMUSE at 11

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locations within the MRB (some of which have experienced a severe mussel population decline in recent years) and one within the St. Croix River Basin, the model was used to simulate scenarios of changing hydrology and sediment loading to determine which basins are most vulnerable to mussel extirpation and identify where management or mitigation efforts would be most effective. The key finding of the model was that mussel populations have a threshold type response to chronic excess suspended sediment. RiverMUSE was further used in the first ever application of information partitioning to environmental time series data (Goodwell & Kumar, 2017b). Information partitioning is an information theory-based method to characterize lagged dependencies between multiple source and target variables, and specifically identify unique (individual), synergistic (joint), and redundant (overlapping) influences in a system. The highly non-linear nature of the RiverMUSE model, in addition to the presence of feedbacks between response variables and driving stressors, provided a testbed for the development of information partitioning techniques for environmental data.

Publicly available streamflow data were used to drive model dynamics, with data reported in section 3.1 (Dolph, Hansen, & Finlay, 2017) used to confirm model parameters. Results showed that if the regimes of increased streamflow and sediment loads observed in the most recent decades continue, mussels may be extirpated in several streams. Model sensitivity to uncertain parameters was also assessed using sensitivity analysis as reported in Hansen, Czuba, et al. (2016). The model is available from CSDMS at (Schwenk, 2018).

5. Innovative New Data Analysis Methods

Although many of the data sets and models were developed with a specific focus on the MRB, a series of innovative data analysis tools and methods that are more portable to other landscapes were also developed. High-resolution lidar data provide immense possibility, but extracting relevant data often requires new tools (i.e., Passalacqua et al., 2015). Several new tools developed as part of the REACH project focus on extracting information from remote spatial data, like the TerEX tool that automatically maps and extracts river terraces from lidar data (i.e., Figure 3; Stout & Belmont, 2014) and Yan et al.'s (2018) extension that distinguishes between riverine floodplains and terraces by transforming the transverse cross-sectional geometry of a river valley into a river valley hypsometric curve and linking hydraulic inundation frequency with the features of this curve. More broadly, the RivMAP (River Morphodynamics from Analysis of Planforms) Matlab package analyzes changes in channel planform over time from remotely mapped channel delineations tracking channel centerlines, widths, migration rates, areas of erosion and accretion, and locations of meander cutoffs (Schwenk et al., 2017). In addition, methods of analyzing river topology and the underlying landscape topography via two-dimensional wavelet transform and synthesis (Danesh-Yazdi et al., 2017) as well as river hydrochemistry using dynamic travel time distributions (i.e., Danesh-Yazdi et al., 2016; Foufoula-Georgiou et al., 2015; Goodwell & Kumar, 2017a, 2017b) in conjunction with information partitioning and other nonparametric analyses provide templates for analyses of other systems that have been impacted by intensive management.

Kumarasamy and Belmont (2018) argue for more robust and targeted calibration of hydrologic models and developed the Hydrology Model Evaluation Toolbox to guide model calibration procedures along with a suite of analytical tools to facilitate calibration and minimize problems of equifinality. Specifically, they show that different information contained in the time and frequency domains of streamflow signals can provide complementary insights to guide selection of parameters adjusted during calibration. The Hydrology Model Evaluation toolbox facilitates evaluation of hydrologic models based on a wide range of metrics, including full distributions of performance metrics evaluated at daily time steps, rather than simple averages, and uses of Euclidian distance, empirical quantile-quantile plots, and flow duration curves to identify and localize errors in model simulations and ensure that models are calibrated well for the specific flows of interest.

6. Collaborative Integration of Scientific Understanding Into Curriculum for Local Students in Their Home Landscapes

In addition to biophysical data collection and modeling, our interdisciplinary research was integrated with an educational component (entitled “RiverRun”), to engage K-12 students and teachers in learning about critical environmental issues and actively participating in service learning related to environmental action. In response to calls from the NSF Advisory Committee for Environmental Research and Education (2009), RiverRun focused on curriculum that “integrates disciplines into a holistic perspective of Earth's natural and human systems.” Curricular units were developed and tested in collaboration with local teachers and focused on improving environmental literacy and student learning (https://sites.google.com/a/umn.edu/riverrun/home).

The curricular work focused on (i) socioscientific issues (SSIs) and (ii) Earth systems thinking. One of the primary goals was to enable students to use their understanding of science to make informed decisions about SSIs that impact their lives. We found that involvement in a curriculum focused on SSIs related to environmental issues within the MRB improved secondary students' (i) environmental literacy (Karahan & Roehrig, 2016, 2017), (ii) understanding of scientific practices, cultural and social influences on science, and scientific bias (Karahan & Roehrig, 2017), and (iii) ability to make informed decisions on environmental issues by applying multiple modes of reasoning (Karahan et al., 2016; Karahan & Roehrig, 2017). Earth systems-oriented approaches focus on promoting understanding of complex scientific phenomena including those found within the MRB. Specifically, we focused on how carbon and nitrogen cycles are impacted by agricultural practices through a combination of inquiry-based lessons and the computer simulation described in section 4.2 (http://maps.umn.edu/le-sueur-nitrates/). Through this effort, data collection and modeling were integrated in real time into educational approaches designed to help improve student understanding of systems behavior.

7. Discussion: Opportunities Enabled by Observatory-Scale Efforts

Environmental problems increasingly require complex transdisciplinary solutions. Over time, long-term environmental research sites have been developed across a wide range of biomes through programs like the Long-Term Ecological Research network and the National Ecological Observatory Network to focus on ecological and socioecological systems (e.g., S. L. Collins & Childers, 2014; Goodman et al., 2015; Hobbie et al., 2003; Redman et al., 2004; Utz et al., 2013). More recently CZOs focusing on the physical, biogeochemical, and ecological interactions within the Earth's critical zone have been developed, bringing more geoscience into the observatory platform (e.g., Anderson et al., 2008; White et al., 2015; Wilson et al., 2018). Many of these observatory efforts are funded for decades, with a goal of developing long-term environmental data sets for cutting-edge transdisciplinary science. These observatories are able to install long-term monitoring stations, with networks like National Ecological Observatory Network and CZOs collecting common data sets across sites for cross-site comparisons (e.g., Goodman et al., 2015; Utz et al., 2013; White et al., 2015). These efforts that are both long-term and broad-based can build impressive and important data sets over time to be utilized to study a variety of environmental processes and feedbacks.

The REACH project was a much shorter-term (5-year) initiative in a large watershed, and as such it offers a model for how to leverage existing research and public data to produce observatory-scale multidisciplinary advances across a broad area over a much shorter timeframe. First of all, data collection within the REACH project was overlain upon an extensive network of gaging stations run by state and federal agencies (see Table S1). Much of this network was developed through the foresight of state agency scientists who identified the need for more intensive data collection in areas of the basin that were producing the highest loads and concentrations of sediment, nitrate, and phosphorus (Musser et al., 2009). This gave both a wide spatial coverage and a longer temporal coverage. Combining gaging data with meteorological data and land use/land cover data, for example, led to discoveries on the links between the timing of crop conversion (as a proxy for drainage) and changes in hydrologic connectivity and system response across the MRB (Foufoula-Georgiou et al., 2015) and the ability to quantify changes in rainfall-runoff relationships over time (Kelly et al., 2017; Novotny & Stefan, 2007). Second, the REACH project built upon previous research efforts into sediment sources and geomorphic history within the Le Sueur subwatershed (Belmont et al., 2011; Gran et al., 2009, 2013). This provided a solid geomorphic framework in which to overlay future interdisciplinary data collection and modeling efforts. Third, data collection and analyses were tiered spatially, with more intensive monitoring and analysis in a few key subwatersheds within the Minnesota River. In the Le Sueur, for instance, we were able to combine the earlier work on sediment sources with intensive biogeochemical data collection to look at the role of sediment on phosphorus sources and transformations (Baker, 2018). We also focused our most intense modeling efforts in the Le Sueur (Cho et al., 2017, 2018; Czuba et al., 2017, 2018). Lastly, partnering with the IML-CZO increases both the ability to compare results from the MRB with other intensively managed agricultural watersheds and the potential to link discoveries in critical zone research from the IML-CZO field sites with the most intensive monitoring (Upper Sangamon River in Illinois and Clear Creek in Iowa) back to the MRB. As more calls go out for continental-scale data to understand environmental system behavior under a changing climate (Hinckley et al., 2016; Murdoch et al., 2014; Peters et al., 2014; Richter et al., 2018), projects like REACH play an important role in expanding the spatial coverage of longer-term network-scale research efforts into large watersheds.

The opportunity to collect and analyze a wide array of environmental data in a large, intensively managed watershed has already led to scientific insights ranging from quantifying changes in hydrologic connectivity and system response (Foufoula-Georgiou et al., 2015), to identifying the importance of hydrologic change on erosion of near-channel sediment sources and associated nutrients (Baker, 2018; Kelly & Belmont, 2018; Vaughan et al., 2017), and to highlighting the ways in which biogeochemical processes can alter pollutant export behavior (e.g., Czuba et al., 2018; Hansen et al., 2018). Our research has direct implications in large agricultural watersheds where the source of water quality impairments (e.g., fine sediment, nitrate, or phosphorus) is spatially complex and may involve the interference of multiple stressors on the landscape (i.e., intensive agriculture, climate change, and loss of wetlands). It is critical to know both the drivers of the impairment as well as the spatial extent of the source, particularly when only a small fraction of the area contributes a disproportionate amount of a given pollutant. Given these complexities, our research has highlighted the need to strategically collect observations and develop watershed-scale models that capture the essential process dynamics and be used in collaboration with stakeholders to guide conservation management and design. In particular, the collection of original field data sets and subsequent modeling efforts described here cumulatively point to the importance of local amplification or dampening within a watershed that requires explicit representation of features such as channels and wetlands, which can mobilize near-channel sediments or serve as ecosystem control points (sensu Bernhardt et al., 2017) affecting delivery at the watershed scale.

Many of our research findings have immediate and direct implications on federal and state policies, planning, and restoration strategies. For example, our approach has demonstrated the enormous potential for wetlands to abate nitrogen and sediment transport at watershed scales (Cho et al., 2019; Hansen et al., 2018; Mitchell et al., 2018), with wetland installation shown to be 5 times more effective at reducing nitrate than field-based approaches (i.e., cover crops) under high to moderate flows (Hansen et al., 2018). At the same time, stakeholder-driven modeling of management options to reduce sediment loading enabled consensus agreement among our stakeholder group for hydrology management to be included as an integral part of management portfolios focused on sediment reduction (Cho et al., 2017). Although recent federal policy directives assigning no societal importance to the value of wetlands (Boyle et al., 2017) runs contrary to these findings, the science-based decision-making approaches have shifted Minnesota toward a stronger focus on water retention in the landscape to mitigate nitrogen, reduce peak flows, and lower erosion rates (i.e., Lewandowski et al., 2015). While more work is needed on this front, our research in the MRB, in close collaboration with stakeholders, has already affected how state agencies plan to address management options needed to meet the required targets of nutrient loads as recommended by the Gulf of Mexico Hypoxia Task Force (Scavia et al., 2017).

Advances described here were made possible through funding by NSF's Water Sustainability and Climate program, which allowed a multidisciplinary and multi-institutional team of researchers to pursue a combination of field data collection, innovative data analysis methods, and the development of data-driven reduced complexity models for scientific understanding and guiding management decisions. Even though the funding was relatively short term compared to larger observatory-scale efforts, we show how focused data collection in subwatersheds overlain on a broader network of public monitoring data can broaden both the temporal and spatial reach of the field data collection effort. We consider our project as a prime example of the benefits of collaborative interdisciplinary research in which the collective outcome is larger than the sum of the parts and which gains enough momentum to affect management and policy, producing young scientists trained to appreciate the power of research across disciplines to handle challenging environmental problems.

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