AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2017WR020839

Special Section:
Earth and Space Science is Essential for Society

Solving water quality problems in agricultural landscapes: New approaches for these nonlinear, multiprocess, multiscale systems

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Abstract Changes in climate and agricultural practices are putting pressure on agroenvironmental systems all over the world. Predicting the effects of future management or conservation actions has proven exceptionally challenging in these complex landscapes. We present a perspective, gained from a decade of research and stakeholder involvement in the Minnesota River Basin, where research findings have influenced solutions and policy in directions not obvious at the outset. Our approach has focused on identifying places, times, and processes of accelerated change and developing reduced complexity predictive frameworks that can inform mitigation actions.

Key Points:
- Changes in climate and land use cascade through agricultural systems in complex ways intensifying challenges in meeting water quality goals
- Effective solutions emerge from understanding the system and identifying hot spots and feedback loops where efforts would do the most good
- Physical and process connectivity is fundamental in upscaling from a field to the watershed scale for effective management strategies

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Citation:
Belmont, P., and E. Foufoula-Georgiou (2017), Solving water quality problems in agricultural landscapes: New approaches for these nonlinear, multiprocess, multiscale systems, *Water Resour. Res.*, *53*, doi:10.1002/2017WR020839.

Received 4 APR 2017
Accepted 7 APR 2017
Accepted article online 20 APR 2017

1. Critical Challenges in Science, Policy, and Management in Agricultural Landscapes

Agricultural systems all over the world are undergoing pervasive changes in climate and land use-land cover. For example, the intensively managed agricultural landscapes of the Midwestern U.S., which contribute 40% of the global corn and soybean supply from less than 1% of the Earth's land area [*Guanter et al.*, 2014], have transitioned from mostly wheat and small grains to the more profitable corn and soybeans in the last few decades [e.g., *Musser et al.*, 2009; *Foufoula-Georgiou et al.*, 2015]. In addition to changing crop choice, farmers have modified tillage operations, fertilizer application, artificial drainage, and conservation practices (collectively called land use-land cover LULC change) to optimize production. Climate change has also strongly influenced these systems. For example, warmer temperatures and altered timing-frequency-magnitude of storms on top of LULC change have significantly altered the water, sediment, carbon, and nutrient dynamics in these landscapes, adversely impacting the quality and ecological integrity of the receiving waters [*Wood and Armitage*, 1997; *Bilotta and Brazier*, 2008; *Finlay*, 2011]. Agroenvironmental systems respond to such changes in complex ways. Threshold effects and nonlinear processes can lead to unanticipated consequences, which may take several years to be realized [e.g., *Rabalais et al.*, 1996; *Tilman et al.*, 2001; *Van Oost et al.*, 2007; *Wilkinson and McElroy*, 2007].

Understanding and predicting the interactions between the atmosphere, land-surface, water system, built environment, and ecosystem function and services is one of the greatest challenges of this century. Realistically, understanding the full suite of interactions is out of reach at present, emphasizing the need to embrace an approach that focuses on the essential processes, places, and times that would most effectively dictate where conservation, mitigation, and adaptation strategies will do the most good.

Finding ways to identify critical processes and areas in a landscape that are most vulnerable to change is an intriguing topic for researchers, but it is vital for managers and policymakers, whose decisions may have profound and long-lasting effects on the economic prosperity and environmental integrity of the region. Furthermore, it is difficult, and likely unsustainable to attempt to implement large-scale changes in policy and management without adequate understanding and acceptance by individual land owners, whose day-to-day actions contribute to, or help prevent, environmental and ecological degradation and whose choices on election day empower decision makers.

The science and engineering community can play a transformative role in providing essential understanding of these complex socioecological systems, how they will respond to future perturbations, and what states or thresholds should be avoided to keep the system within desired environmental boundaries. However, the process of "science informing policy and management" is a two way street. It only works if the scientific information is both reliable and communicated effectively. At the same time, people in the critical policy and management positions must fundamentally embrace science as a means to understand the world and be committed to applying the best available information as a basis for decision making for the public good.

We were fortunate to have found such a science-embracing decision-making environment in the state of Minnesota. Over the past decade, our research group has leveraged an immense amount of publicly available data, funding sources have enabled development of innovative tools for analysis and modeling, and relationships fostered with stakeholders have resulted in new, promising strategies for improving water quality while maintaining economic viability of an intensively managed agricultural landscape. We describe herein some of the key elements of our success story and give perspectives for the future.

2. New Science, Surprising Results, and Engaging Stakeholders

The Minnesota River Basin (MRB) covers 44,000 km^2 in the Upper Mississippi River Basin and contains an alarming 336 impairments for excessive sediment and nutrients or degraded aquatic life under the USEPA Clean Water Act [*Minnesota Pollution Control Agency*, 2015]. It has been determined that the Minnesota River is the main source of sediment and nutrients to the severely impaired Lake Pepin [*Kelley and Nater*, 2000], a naturally dammed lake on the Mississippi River. The MRB contributes 80–90% of the sediment delivered to Lake Pepin, while contributing a mere 38% of the water discharge to the lake. The proportion of sediment derived from the MRB has been relatively constant over the past 10,000 years, but the sedimentation rate in Lake Pepin has increased tenfold over the past 170 years [*Kelley et al*., 2006; *Engstrom et al*., 2009].

Recognition of the degraded state of the Minnesota River in the 1990s prompted several key questions. Where are the sediment and nutrients coming from? How much is natural versus anthropogenic? Can these rivers be cleaned up, and if so, which actions should be taken, where and at what cost? The answers to those questions have big implications for guiding hundreds of millions of dollars spent annually in conservation, the multibillion dollar agricultural industry, and both quantifiable and unquantifiable economic value of water resources in Minnesota and downstream.

Historically, the Minnesota River Basin was dominated by wetland and tall grass prairie [*Musser et al*., 2009]. A suite of profound transformations converted the landscape into some of the most productive agricultural land in the world, with 78% of the watershed in agricultural land use, mostly corn and soybeans. Thus, it seemed obvious to many that agricultural practices were the cause of the water quality problems and the solution necessarily involved taking vast amounts of land out of production, an expensive proposition that was largely unpopular among agricultural land owners. In 1992, Minnesota Governor Arne Carlson declared that the Minnesota River needed "tremendous improvement" and launched an extensive program to clean up the river. Hundreds of thousands of acres were taken out of production for conservation easements. Over 11,000 sediment and nutrient reduction projects utilizing public funding were completed between 1997 and 2008 [*Musser et al*., 2009]. And yet the sediment and nutrient problems persisted. Were the money and efforts wasted?

Farmers, predictably, preferred the explanation that the excessive sediment loads were instead caused by tall bluffs that lined lower portions of some of the Minnesota River tributaries, which were viewed as "natural" sediment sources. And there was some evidence to suggest that bluff erosion may play a role [*Sekely et al*., 2002], but with measurements on only a few bluffs and large uncertainties in extrapolation, there was little basis to determine how sediment loading from these features compared to that from the vast majority of the landscape covered in row crops. Could the farmers be right?

The stakes were elevated in the November 2008 election when, amidst near-economic meltdown, Minnesotans resoundingly voted in favor of a referendum to raise their own taxes, including an estimated $2 billion by 2034, exclusively for the purpose of improving water quality. It was a substantial, optimistic investment in the future of the state's water resources. If invested wisely, such an investment could remarkably improve water quality throughout the state. If invested poorly, the funding could evaporate, with little if any improvement in water quality. Passing of the referendum was also a resounding vote of confidence in the

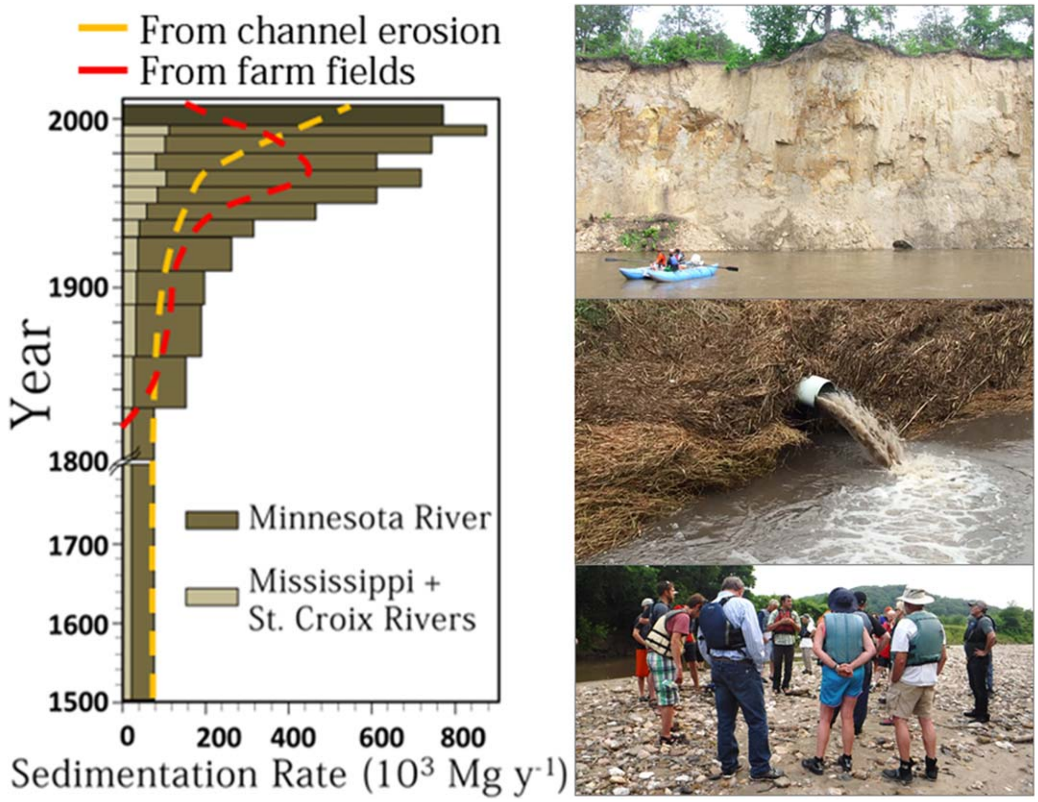

Figure 1. (left) Sedimentation rates (brown bars) measured in Lake Pepin (modified from *Engstrom et al.* [2009]) and interpreted trends for sediment loading from soil erosion on farm fields (red) versus erosion of near-channel features such as bluffs and stream banks (gold), based on sediment fingerprinting results of *Belmont et al.* [2011]. (top right) A 20 m tall bluff composed of glacial till, (middle) a drain tile outlet (credit: Bruce Rhodes), and (bottom) stakeholders on a field trip in the Le Sueur River (credit: Jessica Nelson).

scientific and engineering communities to provide reliable and useful guidance as well as in politicians, state and local agencies, and private land owners to get the job done.

As part of a National Science Foundation (NSF) Science and Technology Center—the National Center for Earth Surface Dynamics (NCED)—a group of interdisciplinary scientists engaged with state agencies and a broader group of scientists studying the intricate questions of the MRB with the determination that science can provide some timely and much needed solutions to the water quality problems of the basin [*Brezonik et al.*, 1999; *Novotny and Stefan*, 2007; *Wilcock*, 2009; *Lenhart et al.*, 2011; *Dalzell et al.*, 2011]. With NCED funding supplemented by a modest amount of state funding, *Belmont et al.* [2011] compiled a sediment budget in the Le Sueur watershed, a 2880 km^2 MRB tributary contributing the largest sediment loads. The sediment budget established that eroding bluffs and stream banks accounted for approximately 70% of sediment loading within the Le Sueur watershed.

To test the hypothesis that sediment coming from bluffs and banks along the river also dominate at much larger spatial scales, *Belmont et al.* [2011] analyzed geochemical tracers in sediment cores from Lake Pepin. They documented a major shift from near-channel sediment sources dominating 170+ years ago, to agricultural field sediments dominating in the mid-twentieth century. But remarkably, while sedimentation rates in Lake Pepin remained high since 1950, *Belmont et al.* [2011] showed that the source of sediment has shifted back to predominately near-channel bluffs and stream banks (Figure 1). In effect, sediment reductions achieved by farmers improving tillage practices and taking land out of production had been entirely offset, as enhanced artificial drainage and increased precipitation amplified erosion of near-channel sediment sources [*Belmont et al.*, 2011; *Lenhart et al.*, 2011, 2013; *Schottler et al.*, 2014; *Foufoula-Georgiou et al.*, 2015; *Kelly et al.*, 2017]. These findings reconciled the opposing views regarding dominant sediment sources, led to development of the hypothesis that anthropogenic climate and LULC change have amplified erosion of otherwise natural features through amplified hydrology, and highlighted the fact that remediation efforts needed to move beyond conventional agricultural field practices to essentially water-reduction management strategies.

Sustained funding over the past 5 years from the National Science Foundation Water Sustainability and Climate (WSC) program has enabled further data collection and model development for better understanding of the system and actionable information for conservation and remediation. Central to our approach have been multiscale analyses, development of reduced complexity models (RCMs) that focus on key processes, and careful attention to transport and transformations within river systems, which modulate environmental signals between the farm field and watershed outlet. For example, *Czuba and Foufoula-Georgiou* [2014, 2015] developed a network-based, sediment routing RCM to identify geomorphic hotspots and "bottlenecks" in river transport systems. *Hansen et al*. [2016a] developed a dynamic, process-based interaction model that couples streamflow, suspended sediment, phytoplankton, and mussel abundance to test hypotheses about limiting factors, identify priority locations for restoration activities, and evaluate the effects of climate-change or land use-change scenarios. *Call et al*. [2017] developed a morphodynamic RCM to simulate how channels change under nonstationary flow and sediment supply and demonstrate the importance of channel adjustment and shifts in variance of the flood flow regime in determining future changes in floodplain inundation and flood risk. *Viparelli et al*. [2013] and *Belmont et al*. [2014] presented RCMs of environmental tracer transport within channel-floodplain systems, which provides an independent constraint on sediment delivery across multiple spatial scales. Combining mapping and dating of fluvial terraces with numerical modeling, *Gran et al*. [2013] expanded our understanding of how sediment loading has changed throughout the Holocene, confirming that near-channel erosion rates are substantially amplified above long-term averages in the Le Sueur River.

These approaches begin to fill a critical gap in predictability. Prominent models used to predict the effects of agricultural practices at the watershed scale have advanced dramatically in sophistication, flexibility in model structure, and representation of management actions [*Santhi et al*., 2014; *Chen and Wu*, 2012; *Gassman et al*., 2007; *Kumarasamy and Belmont*, 2017]. Yet they remain susceptible to deficiencies in methods to scale up from the field scale to large watersheds as well as representation of river channel dynamics, sediment storage, and transport processes, all critical components of the Minnesota River Basin system.

To support development of a watershed-scale sediment reduction strategy in a way that moves beyond conventional models, we convened a diverse group of stakeholders, including individual farmers, agriculture industry representatives, and local and state agency staff for a total of nine meetings over 5 years. We engaged the stakeholders in a participatory modeling effort in which we developed an RCM to estimate annual cost and sediment load reductions associated with user-specified portfolios of conservation practices [*Cho*, 2017]. The model required representation of upland and channel erosion, robust water and sediment routing, and reliable estimates of the extents, costs, and effectiveness of all conservation practices that could plausibly be implemented. Yet the model was designed to be simple and fast, so portfolios could be modified easily and multidecade scenarios run in a few seconds. Unified by the common goals of cleaner water and not wasting money, be it public funding or private land unnecessarily taken out of production, the stakeholder group utilized the model as a basis for understanding and discussing various portfolios of management options. The group produced a consensus document outlining a strategy for sediment reduction, which is currently being circulated to the state legislature, soil water conservation district staff, and nonprofit organizations. Foremost among the recommendations are detention basins and wetlands to be installed in the upper portions of the watershed in order to desynchronize the peaks of storm hydrographs, which translates to a disproportionately large reduction in bluff erosion. Model results suggest that careful targeting of the installation of these water detention features in as little as 5% of the landscape could reduce sediment loading by as much as half. Related work in the same basin suggests that restoring a few percent of the landscape to wetlands could also dramatically reduce nitrate export [*Hansen et al*., 2016b].

All of the above science could have been relegated to a mere academic exercise if Minnesota state agencies had not been thoroughly engaged and responsive to new knowledge. When provided credible and robust information, they were ultimately amenable to changing their perspective on the somewhat diminished role of agricultural field erosion in causing excessive sediment loads. Further, they modified suspended sediment regulations when provided with evidence indicating that background rates of sediment were naturally high in the actively incising lower portions of MRB tributaries. Surface water retention featured prominently in the Minnesota Pollution Control Agency's 2015 Sediment Reduction Strategy for the

Minnesota River Basin [*Minnesota Pollution Control Agency*, 2015] and serves as a guiding principle for the Minnesota Clean Water Council's FY18-19 Policy Recommendations to the State Legislature [*Minnesota Pollution Control Agency*, 2016].

3. The Value of Science-Informed Policy and Management

Conflicts between economic profitability and environmental quality are inevitable and common. We have big decisions to make, with very real and long-lasting implications for both people and the environment. The science and engineering community has a vital role to play in weighing enviroeconomic trade-offs and informing key policy and management decisions. At the same time, we must help the general public understand the value of science, the nonlinear and self-corrective manner in which science progresses, and the robust nature of scientific inquiry and debate. The community has never been better positioned to contribute in this role, with availability of high resolution data, innovative new field and laboratory methods, analytical tools and computational models, and information technology all advancing at an astounding pace over the past decade. Putting these tools in the hands of an amazingly diverse community of creative and motivated individuals ensures continued and accelerated progress. Given the complexity of agroenvironmental systems and the nonlinear manner in which changes propagate through them, we advocate for a new focus on approaches that identify the places, times, and processes of amplified change to guide data collection and reduced complexity modeling to inform conservation and mitigation actions.

Our experience over the past decade in Minnesota highlights that it takes sustained funding, advances in basic, interdisciplinary science, and a considerable time and effort to build a level of trust and understanding between scientists and stakeholders. Developing those relationships, building that trust, and effectively communicating new and actionable insights are paramount, not only for sustaining public and financial support for science but also to guide decisions that enable short-term economic prosperity, while maintaining the integrity of the myriad ecosystem services on which our long-term economic sustainability depends.

Acknowledgments
This work was made possible with support from the National Science Foundation Water Sustainability and Climate (NSF ENG 1209445 and 1209402) and National Center for Earth Surface Dynamics (NSF EAR 0120914), US Department of Agriculture NRCS (69-3A75-14-269), Minnesota Pollution Control Agency, Minnesota Department of Agriculture, the Minnesota Clean Water, Land and Legacy Amendment, and the Minnesota Agricultural Water Resource Center. Peter Wilcock, Karen Gran, Carrie Jennings, Shawn Schottler, Stephanie Day, Se Jong Cho, Sara Kelly, Karthik Kumarasamy, Jon Czuba, and many others contributed to the research discussed. No new data are presented in this commentary. Martyn Clark, Jennifer Lunn, Jean Bahr, and an anonymous reviewer provided constructive reviews that improved the paper.

References

Belmont, P., et al. (2011), Large shift in source of fine sediment in the Upper Mississippi River, *Environ. Sci. Technol.*, *45*, 8804–8810, doi: 10.1021/es2019109.

Belmont, P., J. K. Willenbring, S. P. Schottler, J. Marquard, K. Kumarasamy, and J. Hemmis (2014), Toward generalizable sediment fingerprinting with tracers that are conservative and non-conservative over sediment routing timescales, *J. Soils Sediments*, *14*(8), 1479–1492, doi:10.1007/s11368-014-0913-5.

Bilotta, G. S., and R. E. Brazier (2008), Understanding the influence of suspended solids on water quality and aquatic biota, *Water Res.*, *42*(12), 2849–2861.

Brezonik, P. L., K. W. Easter, L. Hatch, D. Mulla, and J. Perry (1999), Management of diffuse pollution in agricultural watersheds: Lessons from the Minnesota River Basin, *Water Sci. Technol.*, *39*(12), 323–330.

Call, B., P. Belmont, J. C. Schmidt and P. R. Wilcock (2017), Changes in floodplain inundation under non-stationary hydrology for an adjustable, alluvial river channel, *Water Resour. Res.*, *53*, doi: 10.1002/2016WR020277, in press.

Chen, J., and Y. Wu (2012), Advancing representation of hydrologic processes in the Soil and Water Assessment Tool (SWAT) through integration of the TOPographic MODEL (TOPMODEL) features, *J. Hydrol.*, *420–421*, 319–328, doi:10.1016/j.jhydrol.2011.12.022.

Cho, S. J. (2017), Development of data-driven, reduced-complexity watershed simulation models to address agricultural non-point source sediment pollution in southern Minnesota, PhD dissertation, The Johns Hopkins Univ., Baltimore, Md.

Czuba, J. A., and E. Foufoula-Georgiou (2014), A network-based framework for identifying potential synchronizations and amplifications of sediment delivery in river basins, *Water Resour. Res.*, *50*, 3826–3851, doi:10.1002/2013WR014227.

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

Dalzell, B. J., J. Y. King, D. J. Mulla, J. C. Finlay, and G. R. Sands (2011), Influence of subsurface drainage on quantity and quality of dissolved organic matter export from agricultural landscapes, *J. Geophys. Res.*, *116*, G02023, doi:10.1029/2010JG001540.

Engstrom, D. R., J. E. Almendinger, and J. A. Wolin (2009), Historical changes in sediment and phosphorus loading to the upper Mississippi River: Mass-balance reconstructions from the sediments of Lake Pepin, *J. Paleolimnol.*, *41*(4), 563–588, doi:10.1007/s10933-008-9292-5.

Finlay, J. C. (2011), Stream size and human influences on ecosystem production in river networks, *Ecosphere*, *2*(8), 1–21.

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

Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold (2007), The soil and water assessment tool: Historical development, applications, and future research directions, *Trans. Am. Soc. Agric. Biol. Eng.*, *50*(4), 1211–1250.

Gran, K. B., N. Finnegan, A. L. Johnson, P. Belmont, C. Wittkop, and T. Rittenour (2013), Landscape evolution, valley excavation, and terrace development following abrupt postglacial base level fall, *GSA Bull.*, *125*(11–12), 1851–1864.

Guanter, L., Y. Zhang, M. Jung, J. Joiner, M. Voigt, J. A. Berry, C. Frankenberg, A. R. Huete, P. Zarco-Tejada, and M. S. Moran (2014), Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence, *Proc. Natl. Acad. Sci.*, *111*(14), E1327–E1333.

Hansen, A. T., J. A. Czuba, J. Schwenk, A. Longjas, M. Danesh-Yazdi, D. J. Hornbach, and E. Foufoula-Georgiou (2016a), Coupling freshwater mussel ecology and river dynamics using a simplified dynamic interaction model, *Freshwater Sci.*, *35*(1), 200–215.

Hansen, A. T., C. L. Dolph, and J. C. Finlay (2016b), Do wetlands enhance downstream denitrification in agricultural landscapes?, *Ecosphere*, *7*(10), e01516.

Kelley, D. W., S. A. Brachfeld, E. A. Nater, and H. E. Wright (2006), Sources of sediment in Lake Pepin on the upper Mississippi River in response to Holocene climatic changes, *J. Paleolimnol.*, *35*(1), 193–206.

Kelley, D. W., and E. A. Nater (2000), Historical sediment flux from three watersheds into Lake Pepin, Minnesota, USA, *J. Environ. Qual.*, *29*(2), 561–568.

Kelly, S., Z. Takbiri, P. Belmont, and E. Foufoula-Georgiou (2017), Human amplified changes in precipitation-runoff patterns in large river basins of the Midwestern United States, *Hydrol. Earth Syst. Sci.*, doi:10.5194/hess-2017-133, in press.

Kumarasamy, K., and P. Belmont (2017), Multiple domain evaluation of watershed hydrology models, *Hydrol. Earth Syst. Sci.*, doi:10.5194/hess-2017-121, in press.

Lenhart, C. F., E. S. Verry, K. N. Brooks, and J. A. Magner (2011), Adjustment of prairie pothole streams to land-use, drainage and climate changes and consequences for turbidity impairment, *River Res. Appl.*, *28*, 1609–1619, doi:10.1002/rra.1549.

Lenhart, C. F., M. L. Titov, J. S. Ulrich, J. L. Nieber, and B. J. Suppes (2013), The role of hydrological alteration and riparian vegetation dynamics in channel evolution along the Lower Minnesota River, *Trans. Am. Soc. Agric. Biol. Eng.*, *56*(2), 549–561.

Minnesota Pollution Control Agency (2015), *Sediment Reduction Strategy for the Minnesota River Basin and South Metro Mississippi River*, St. Paul, Minn. [Available at https://www.pca.state.mn.us/sites/default/files/wq-iw4-02.pdf.]

Minnesota Pollution Control Agency (2016), *Clean Water Council FY18-19 Clean Water Fund and Policy Recommendations Report Biennial Report to the Legislature*, St. Paul, Minn. [Available at https://www.pca.state.mn.us/sites/default/files/lr-cwc-1sy16.pdf.]

Musser, K., S. Kudelka, and R. Moore (2009), *Minnesota River Basin Trends Report*, 66 pp., Minnesota State University at Mankato Water Resource Center, Mankato, Minn. [Available at http://mrbdc.wrc.mnsu.edu/mnbasin/trends/index.html.]

Novotny, E. V., and H. G. Stefan (2007), Stream flow in Minnesota: Indicator of climate change, *J. Hydrol.*, *334*(3–4), 319–333.

Rabalais, N. N., R. E. Turner, D. Justić, Q. Dortch, W. J. Wiseman, and B. K. Sen Gupta (1996), Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf, *Estuaries Coasts*, *19*(2), 386–407.

Santhi, C., et al. (2014), Effects of agricultural conservation practices on N loads in the Mississippi–Atchafalaya River Basin, *J. Environ. Qual.*, *43*, 1903–1915, doi:10.2134/jeq2013.10.0403.

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

Sekely, A. C., D. J. Mulla, and D. W. Bauer (2002), Streambank slumping and its contribution to the phosphorus and suspended sediment loads of the Blue Earth River, Minnesota, *J. Soil Water Conserv.*, *57*, 243–250.

Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, and D. Swackhamer (2001), Forecasting agriculturally driven global environmental change, *Science*, *292*(5515), 281–284.

Van Oost, K., et al. (2007), The impact of agricultural soil erosion on the global carbon cycle, *Science*, *318*(5850), 626–629.

Viparelli, E., J. W. Lauer, P. Belmont, and G. Parker (2013), A numerical model to develop long-term sediment budgets using isotopic sediment fingerprints, *Comput. Geosci.*, *53*, 114–122.

Wilcock, P. R. (2009), Identifying sediment sources in the Minnesota River Basin, in *Minnesota River Sediment Colloquium Report*, pp. 1–18, Minn. Pollut. Control Agency, St. Paul, Minn. [Available at https://www.pca.state.mn.us/sites/default/files/wq-b3-43.pdf, accessed online April 18, 2017.]

Wilkinson, B. H., and B. J. McElroy (2007), The impact of humans on continental erosion and sedimentation, *Geol. Soc. Am. Bull.*, *119*(1–2), 140–156.

Wood, P. J., and P. D. Armitage (1997), Biological effects of fine sediment in the lotic environment, *Environ. Manage.*, *21*(2), 203–217.