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A program of the Center for Watershed Protection, Inc.

Integrating Climate Change Science into Watershed and Stormwater Management

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8390 Main St. 2nd Floor • Ellicott City, MD 21043 • 410-461-8323 (phone)
410-461-8324 (fax) • www.awsps.org • Bulletin@awsps.org

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This photo was taken along Young's Bay estuary in Astoria, OR. The Young's Bay estuary is a component of the Columbia River estuary, a nationally significant estuary in the northwest corner of Oregon that supports some of the largest anadromous fish runs in the world and provides unique habitat for sensitive and endangered species.

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Increased Streamflow in Agricultural Watersheds of the Midwest: Implications for Management

Christian F. Lenhart[a]*, Heidi Peterson[b], and John Nieber[c]

Abstract

Traditionally, flows that did not cause flooding were thought to be inconsequential for agricultural watershed management. However, flow volume plays an important role in flow duration and Total Maximum Daily Loads (TMDLs), particularly for nitrate-nitrogen. Prolonged below-bankfull flows may also increase bank saturation and the frequency of mass wasting, leading to increased sediment and phosphorous loading and reduced index of biotic integrity scores. Low, mean, and high flows below the bankfull elevation have increased in many upper midwestern watersheds in the past 30 years, although large floods have not increased significantly at most of our study sites. Using the indicators of hydrologic alteration suite of statistical metrics, we found that streamflow has increased in agricultural watersheds (> 67% agricultural land use) in annual mean flow, most monthly median values, and many flow duration metrics during the 1980–2009 time period compared to 1940–1979. As a percentage, flow has increased most in December and least in August through October. At the same time, the streamflow-to-precipitation (Q:P) ratio has increased in the past three decades compared to the previous several decades. The overall change in Q:P, the timing of increased flow, and the reduced streamflow variability, as measured by the coefficient of variation, suggest a mechanism of subsurface tile flow and/or increased groundwater flow. Management actions are needed in agricultural watersheds of the Upper Midwest to reduce water volume as well as peak flow to meet TMDL requirements.

Introduction

Extreme high and low flows have been the primary focus of watershed management, particularly from the water resources engineering perspective (Mays 2001). Global circulation models (GCMs) for climate change predict that extreme events and flow variability will increase, making them even more important from a management perspective. Both floods and extreme low flows have clear consequences for humans and for aquatic biota. Consequently, management approaches for addressing these problems are well established in the field of watershed management (Mays 2001; Brooks et al. 2003).

In contrast, the watershed management field has not made a widespread effort to manage flows below the bankfull level in agricultural watersheds because many in the field believe that their impacts are minimal. Nevertheless, increased low and mean flows have occurred recently in many upper midwestern watersheds concurrently with climatic and land use changes. Despite the lack of management, less-than-flood-level flows are important because they increase the duration of high flow, adding to the cumulative transport of sediment and nutrients and increasing annual loads (Cleland 2002). This has crucial implications for total maximum daily loads (TMDLs) and nutrient management issues. For example, the Gulf of Mexico hypoxia problem is primarily caused by excess nitrates—a pollutant carried in dissolved form (Goolsby et al. 2000). The cumulative loading of dissolved substances in the Mississippi River is directly related to the amount of streamflow (Donner et al. 2004; Raymond et al. 2008). Streamflow volume increases have become an issue in urban stormwater management (Minnesota Pollution Control Agency [MPCA] 2005) and are being addressed with infiltration practices in some areas.

Increased flows below the bankfull level also may have important impacts on stream ecology and channel stability (Richter et al. 1996). Sediment and particulate phosphorus loading may increase from prolonged flow duration since bank failure events tend to occur more frequently following saturation of streambanks, when stability conditions are at their lowest (Thorne 1999). Therefore increased streamflow levels will tend to promote more frequent mass wasting events, even below bankfull events.

The Minnesota River Basin (MRB), a focal area for this research, illustrates how watershed response to climate change may not fit preconceived notions based on generic GCM predictions. Watersheds in different regions respond variably to climate changes because runoff and other hydrologic processes are mediated through the unique combinations of the existing land cover, geology, and surface and subsurface drainage networks.

[a] Research Assistant Professor, Department of Bioproducts and Biosystems Engineering, University of Minnesota–Twin Cities, St. Paul, MN, lenh0010@umn.edu

[b] Graduate Research Assistant, Department of Bioproducts and Biosystems Engineering, University of Minnesota–Twin Cities

[c] Professor, Department of Bioproducts and Biosystems Engineering, University of Minnesota–Twin Cities

* Corresponding author.

Methods

We used two complementary statistical approaches to analyze streamflow trends and changes to watershed hydrologic processes in the upper midwestern states, focusing around Minnesota (Figure 1). The indicators of hydrologic alteration (IHA) test for changes in streamflow that may be of ecological importance by comparing two periods of time—before and after a chosen impact, alteration, or climatic change (Richter et al. 1996). In this study, we completed an IHA analysis at 18 watersheds to compare the time periods 1940–1979 and 1980–2009. These time periods capture the longest period of streamflow conditions that are desirable when assessing hydrologic alteration from anthropogenic sources available starting after the Dust Bowl, a period of anomalously low precipitation (Schubert et al. 2004). Of the 16 sites, 13 had stream discharge records dating back to 1940, and three sites (Bois Brule, Sturgeon, and Pigeon) were missing several years from the early 1940s. We conducted significance testing using a boot strapping–like approach whereby the data are reshuffled many times to create a larger population by which to assess significance at the 0.05% level.

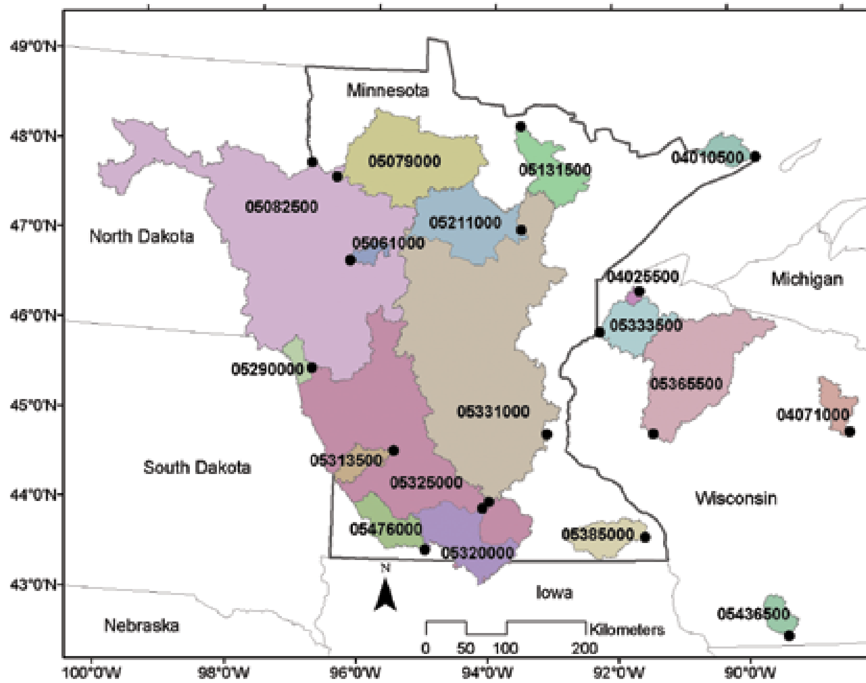

Figure 1. Location of US Geological Survey gauging stations and their corresponding watershed drainage areas included in the indicators of hydrologic alteration and streamflow-to-precipitation ratio analyses.

We analyzed the streamflow-to-precipitation (Q:P) ratio, that describes the percentage of streamflow resulting from precipitation, in more detail on a data subset consisting of the four watersheds located within the MRB. We hypothesized that the Q:P ratio would be indicative of a change in hydrologic process, not just climatic variation. An increase in the Q:P ratio from land use change indicates human alteration rather than climate changes. If a watershed experiences increased streamflow without a concurrent increase in rainfall, clearly some change in land use, drainage, or water withdrawal has altered the Q:P ratio. Both rainfall and runoff are subject to widely varying climatic fluctuations.

We selected the MRB because large changes in streamflow have occurred there, contributing to increased nutrient and sediment loading to the Mississippi River. We selected four watersheds with varying drainage areas located within the MRB based on the availability of long-term streamflow data. We calculated Q:P ratios for these watersheds using mean annual discharge (Q) and precipitation (P) values. We obtained discharge data through the Surface Data for Minnesota website of the US Geological Survey (USGS n.d.). We obtained precipitation data for the climate divisions overlapping the MRB watersheds through the Western Regional Climate Center (n.d.). To address watersheds that overlap several climate divisions, we calculated mean monthly and annual precipitation using the Thiessen polygon method. We then converted precipitation and streamflow to volumes using the watershed drainage area to obtain a Q:P ratio.

To identify whether Q:P ratios have changed over time, we calculated ratios using seasonal (lumped three-month time periods) and annual data. To eliminate any discharge data gaps and to keep relatively consistent time intervals, the two data periods used in the Q:P analysis were 1950–1979 and 1980–2008. We completed the seasonal and annual analyses using a Mann–Whitney nonparametric test of significance to determine if the two time periods have the same distribution of Q:P ratios. We defined seasons as winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November).

We examined the response of upper midwestern watersheds to recent climate change in the form of precipitation increases to better understand potential future responses to climate change, assuming that the hydrologic processes at work will be the same in the future, although possibly varying in scale. We used Minnesota's ecoregion divisions to assess the relative response of different regions to climate change and to identify hydrologic management issues specific to streams in those regions. In particular, we examined in more detail the management consequences for large increases in the Q:P ratio experienced in the southern agricultural watersheds, focusing on the control of streamflow volume in these watersheds. We also briefly examined summer low flow in streams along the north shore of Lake Superior in the northern forested region.

Findings

Mean annual flows have increased in most of the MRB and Red River basin streams as well as in the Des Moines, Sugar, and Root Rivers—specifically, in all watersheds dominated by agricultural land cover (Table 1). Mean annual flow either decreased or did not increase significantly in each of the northern Minnesota and Wisconsin watersheds with more than 67% forest land cover.

Median monthly flows have increased in most months in watersheds with > 67% agricultural land cover (Table 1). The months with the lowest percentage increase were April

Table 1. Summary data for the IHA analysis of 16 watersheds in Minnesota, Wisconsin, and the eastern Dakotas. Flow in the 1980–2009 time period is compared to that of the 1940–1979 time period by the percentage (%) change in the magnitude or number of months with significant change.

Station Location	USGS Gauging Station #	Predominant Land Use Category (%)	Change in Mean Annual Flow (%)	Change in Coefficient of Variation (%)	Months with a Significant Median Monthly Change (% of 12 Months)	Months with a Significant Low-Flow Change (% of 12 Months)
Blue Earth River at Mankato, MN	05320000	> 67 ag	73	–29	83	42
Bois Brule at Brule, WI	04025500	> 67 forest	–2	–13	92	17
Buffalo River at Hawley, MN	05061000	mixed	42	–7	67	67
Chippewa River at Chippewa Falls, WI	05365500	> 67 forest	–7	5	8	–42
Des Moines at Jackson, MN	05476000	> 67 ag	100	–26	83	50
Little Fork River at Little Fork, MN	51315000	> 67 forest	–8	–14	42	42
Little Minnesota River at Peever, SD	05290000	> 67 ag	27	–33	100	100
Minnesota River at Mankato, MN	05325000	> 67 ag	75	–23	92	75
Mississippi River at St. Paul, MN	05331000	mixed	31	–11	50	33
Mississippi at Grand Rapids, MN	05211000	> 67 forest	4	–7	0	0
Oconto River at Gillett, WI	04071000	> 67forest	–9	–11	0	8
Pigeon River at Grand Portage, MN	04010500	> 67 forest	–9	–13	33	33
Red River at Grand Forks, ND	05082500	> 67 ag	56	–10	75	33
Red Lake River at Crookston, MN	05079000	> 67 ag	6	–6	17	8
Root River near Houston, MN	05385000	mixed	57	–36	100	83
St. Croix River at Grantsburg, WI	05333500	> 67 forest	–6	–7	0	0
Sugar River at Brodhead, WI	05436500	> 67 ag	29	–32	92	100
Yellow Medicine River at Granite Falls, MN	05313500	> 67 ag	77	–38	92	58

and August to October; (Figure 2). Low flows increased in 42%–100% of months in streams within the MRB, as well as the Des Moines, Root, and the Buffalo Rivers (the latter is a Red River tributary). In contrast, the northern forested watersheds had low-flow increases in the winter months, but total annual streamflow volume, as indicated by mean annual flow, actually decreased in most cases. The cause of low-flow increases in northern forested watersheds of the Midwest is not well understood. It may be related to warmer temperatures at the beginning and end of the winter season reducing the frozen period (Johnson and Stefan 2006). As a consequence of earlier snowmelt, streamflow in the late spring and summer may be reduced as the timing of streamflow has shifted. Low flows have negative impacts on recreational fishing in streams along the North Shore of Lake Superior, such as the Pigeon River (USGS gauging station 04010500). Streamflow variability, measured by the coefficient of variation, decreased in 15 of 16 streams during the current time period.

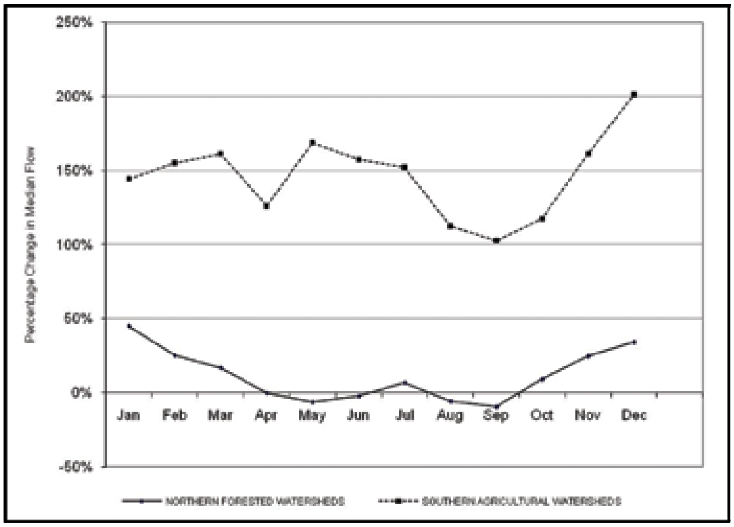

Figure 2. Median monthly flow increases by percentage change during 1980–2009 vs. 1940–1979 in the northern forested watersheds (> 67% forest cover) and the southern and western agricultural watersheds (> 67% agricultural land cover). Each value is an average from all watersheds in Table 1 in each land cover category.

Results of the Mann–Whitney test indicate that the annual Q:P ratios significantly increased in three of the four MRB watersheds from 1950–1979 to 1980–2008 (Table 2). Little Minnesota River near Peever, South Dakota (USGS gauging station 5290000), is the smallest of the four watersheds and also had missing streamflow data during 1982–1989 and after 2003.

Seasonal results of the Mann–Whitney analysis indicated that Q:P ratios in three of the four MRB watersheds significantly increased (p-value < 0.05) from 1950–1979 to 1980–2008 in spring, fall, and winter (Table 3). Summer was the only season without a significant difference in any of the Q:P ratios between time intervals. Minnesota River at Mankato, Minnesota (5325000), had significant differences only in fall and winter.

Table 2. Minnesota River basin annual Q:P ratios for the 1950–1979 and 1980–2008 time intervals.

USGS Gauging Station	Mean Annual Discharge (m^3 second^{-1})		Mean Annual Precipitation (cm year^{-1})		Annual Q:P		p-value[a]
	1950–1979	1980–2008	1950–1979	1980–2008	1950–1979	1980–2008	
5290000	1.2	2.0	49.9	57.6	0.06	0.09	0.170
5313500	3.4	5.6	63.1	68.9	0.10	0.15	**0.037**
5320000	22.8	40.8	72.5	81.2	0.15	0.25	**0.005**
5325000	90.7	158.4	64.6	70.7	0.11	0.18	**0.002**

[a] p-values in bold were considered significant at a maximum 0.05 level resulting from a Mann–Whitney nonparametric analysis of annual Q:P ratios.

Table 3. Minnesota River basin seasonal Q:P ratios for the 1950–1979 and 1980–2008 time intervals.

USGS Gauging Station	Analysis Period	Seasonal Q:P Ratio				p-value[a]			
		Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
5290000	1950–1979	0.31	0.02	0.01	0.02	**0.031**	0.588	**0.050**	**0.007**
	1980–2008	0.41	0.05	0.09	0.08				
5313500	1950–1979	0.31	0.06	0.04	0.06	**0.034**	0.200	**0.005**	**0.007**
	1980–2008	0.37	0.10	0.14	0.24				
5320000	1950–1979	1.17	0.41	0.52	0.44	**0.040**	0.077	**0.000**	**0.003**
	1980–2008	1.79	0.69	1.01	1.14				
5325000	1950–1979	0.27	0.08	0.10	0.10	0.075	0.053	**0.001**	**0.004**
	1980–2008	0.36	0.13	0.19	0.26				

[a] p-values in bold were considered significant at a maximum 0.05 level resulting from a Mann–Whitney nonparametric analysis of seasonal Q:P ratios.

Discussion

In streams within the Upper Midwest, flows ranging from low to moderately high (but below the bankfull flow) have increased, yet large floods (greater than ten-year flood) did not increase significantly during the 1980–2009 time period despite significantly more annual precipitation in most watersheds, with the IHA methodology. In the MRB, our results indicate that Q:P ratios are increasing and contributing to greater flow volumes, particularly during late fall and winter. Evapotranspiration is highest during the summer months, which may explain why Q:P ratios did not increase significantly between June and August (Table 3). Though annual precipitation has increased across southern and western Minnesota, this, alone, could not account for the 70% average annual streamflow increase that occurred in the MRB rivers. Much larger precipitation increases would be required to produce such large streamflow increases.

The discharge could have increased as a result of an increase in baseflow or runoff from storm flow. The greatest percentage of flow increase occurred during months that are typically baseflow periods, suggesting that the mechanism for increased flow was some combination of increased subsurface tile drainage and groundwater flow that altered the pathway by which water is delivered to streams (Schilling and Libra 2003; Schilling et al. 2008). In the MRB, the use of tile drainage, which increases baseflow (Fore 2010) has risen drastically since the 1980s. However, tile drainage is not yet prevalent in the Dakotas; this may explain why, although Little Minnesota River near Peever, South Dakota (USGS gauging station 5290000), is in the MRB, the change in the annual Q:P ratio was not significant (Sugg 2007). In Minnesota, streamflow is typically lowest in February and can, therefore, be used as a proxy for baseflow since minimal surface runoff contributes to the total discharge (Ruhl et al. 2002). Although winter precipitation has decreased and mean maximum temperatures remain below freezing, mean February streamflow in the 1980–2008 time interval has increased in each of the MRB watersheds by an average of 170% compared to the 1950–1979 time period.

The MRB demonstrates the interactive effects of land use and climate change. Land use and drainage changes in the past 30 years have increased low to moderately high flows, but not the large floods as predicted in many climate change scenarios, creating a different set of management issues. There is now a need for streamflow volume control practices in upper midwestern watersheds, particularly to reduce loads of nitrate and other dissolved pollutants carried in tile and groundwater flow. In addition to improved nutrient management, these practices will be critical for addressing the Gulf of Mexico hypoxia problem and will require management strategies that differ from those used for volume control in urban areas (MPCA 2005).

The use of perennial crops and native plants that transpire more water can help reduce water yield. Although large land cover changes would require major shifts in policy, incremental changes are possible (Jordan and Warner 2010). March to June is a particularly critical time period in upper midwestern watersheds because the highest streamflow and Q:P ratio occurs at this time. Snowmelt runoff, combined with the increased runoff from relatively bare fields that occurs early in the growing season, leads to greater streamflow in April. The fall months, which experience the greatest increase in Q:P ratio (Table 3), are another critical time period for the reduction of excess water, sediment, and nutrients.

Increased hydrologic storage through the restoration of lakes and wetlands could help reduce flow and nitrate loading (Leach and Magner 1992). Wetlands in the MRB are thought to be particularly effective at reducing small, frequent floods (with less than a two-year recurrence interval), as the largest floods tend to fill all available storage capacity (Miller 1999). To reduce spring outflow from subsurface drainage, controlled or conservation drainage is another tool that may be used to reduce streamflow volume when drainage is not needed for crop growth, particularly during the high-flow season of March to May (Cooke et al. 2008). The technique may apply to surface ditches as well as subsurface pipes.

The hydrologic response of the northern forested regions to slight precipitation increases contrasted sharply with southern agricultural watersheds…

Lower flows have been considered inconsequential to sediment transport and streambank erosion, since floods in the one- to two-year recurrence range are thought to do most of the work in moving sediment and forming channels (Leopold et al. 1964). Yet increased flow durations lead to a greater frequency of mass wasting by prolonging the duration of moderate flows that partially saturate the streambanks and increase the rate of streambank collapse. For example, Odgaard (1987) found that mean daily flow levels at only one-third of the bankfull discharge or higher were related to bank erosion events.

Unfortunately, it is much more difficult to manage increased bank erosion on a large watershed scale because of the time, cost, and labor-intensive nature of most streambank erosion reduction projects. It would be possible to target channel areas producing the most sediment, but in the long-term, the reduction of water yield via watershed management may be the most sustainable solution.

The hydrologic response of the northern forested regions to slight precipitation increases contrasted sharply with southern agricultural watersheds, highlighting the importance of land use and drainage changes for streamflow response in these regions. In northern forested streams, increased winter streamflow and earlier snowmelt runoff may lead to reduced flow later in the summer, creating higher temperatures that are detrimental to numerous fish species. This is likely to be important in northern Minnesota and Wisconsin for recreational fishing in areas such as the north shore of Lake Superior, where sport fishing is a big part of the tourist industry.

Conclusion

The dissimilar response of the southern agricultural watersheds (exemplified by the MRB case study) compared to northern forested watersheds provides insight into the hydrologic processes responsible for streamflow change and related management issues. By examining the hydrologic response to recent climate changes, this analysis provides clues as to how different regions of the Upper Midwest may respond to future climate changes. Future hydrologic responses are being simulated through hydrologic modeling work currently underway. Still, it is unclear whether flows in the Minnesota and Red River basins will continue to increase in upcoming decades or will taper off with the increasingly higher temperatures and greater evaporation predicted by GCMs. Currently, flow volumes and Q:P ratios are increasing at a rate disproportionate to that of precipitation alone in watersheds exhibiting a large expansion of tile drainage in recent decades.. These hydrologic changes represent a management challenge because they have not been perceived as a management issue in the past. It will be necessary to reduce water, nutrient, and sediment yields for TMDLs in many upper midwestern agricultural watersheds for the foreseeable future using some of the management practices discussed in this paper.

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REFERENCES

Brooks, K. N., P. F. Folliott, H. M. Gregersen, and L. F. DeBano. 2003. Hydrology and the management of watersheds. 3rd ed. Ames, IA: Iowa State University Press.

Cleland, B. 2002. TMDL development from the "bottom up"—Part II: Using duration curves to connect the pieces. Proceedings of the Water Environment Federation, National TMDL Science and Policy 2002: 687–697.

Cooke, R. A., G. R. Sands, and. L. C. Brown. 2008. Drainage water management: A practice for reducing nitrate loads from subsurface drainage systems. In Final Report: Gulf hypoxia and local water quality concerns workshop, Upper Mississippi River Sub-basin Hypoxia Nutrient Committee, 19–28. St. Joseph, MI: American Society of Agricultural and Biological Engineers.

Donner, S. D., M. T. Coe, J. D. Lenters, T. E. Twine, and J. A. Foley. 2004. Modeling the impact of hydrological changes on nitrate transport in the Mississippi River basin from 1955 to 1994. Global Biogeochemical Cycles 16(3): 1043.

Fore, Z. 2010. Tile drainage: Research results, economics, and where do we go from here. St. Paul, MN: University of Minnesota Extension Service.

Goolsby, D. A., W. A. Battaglin, B. T. Aulenbach, and R. P. Hooper. 2000. Nitrogen flux and sources in the Mississippi River basin. Science of the Total Environment 248:75– 86.

Johnson, S., and H. Stefan. 2006. Indicators of climate warming in Minnesota: Lake ice covers and snowmelt runoff. Climatic Change 75:421–453.

Jordan, N., and K. D. Warner. 2010. Enhancing the multifunctionality of US Agriculture. BioScience 60(1): 60–66.

Leach, J., and J. A. Magner. 1992. Wetland drainage impacts within the Minnesota River basin. Currents III(2): 3–10.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. San Francisco: W. H. Freeman.

Mays, L. W. 2001. Water resources engineering. New York: John Wiley & Sons.

Miller, R. C. 1999. Hydrologic effects of wetland drainage and land use change in a tributary watershed of the Minnesota River basin: A modeling approach. MS thesis, University of Minnesota–Twin Cities.

Minnesota Pollution Control Agency. 2005. Minnesota stormwater manual. St. Paul, MN: Minnesota Pollution Control Agency.

Odgaard, A. J. 1987. Streambank erosion along two rivers in Iowa. Water Resources Research 23:1225–1236.

Raymond, P. A., N. H. Oh, R. E. Turner, and W. Broussard. 2008. Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. Nature 451:449–452.

Richter, B. D., J. V. Baumgartner, J. Powell, and D. P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10(4): 1163–1174.

Ruhl, J. F., R. Kanivetsky, and B. Shmagin. 2002. Estimates of recharge to unconfined aquifers and leakage to confining aquifers in the seven-county metropolitan area of Minneapolis–St. Paul, Minnesota, United States. Water Resources Investigations Report 02-4092. Reston, VA: US Geological Survey.

Schilling, K. E., M. K. Jha, Y.-K. Zhang, P. W. Gassman, and C. F. Wolter. 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. Water Resources Research 44:W00A09.

Schilling, K. E., and R. D. Libra. 2003. Increased baseflow in Iowa over the second half of the 20th century. Journal of the American Water Resources Association 39(4):851–860.

Schubert, S. D, M. J. Suarez, P. J. Pegion, R. D. Koster, and J. T. Bacmeister. 2004. On the cause of the 1930s Dust Bowl. Science 303(5665): 1855–1859.

Sugg, Z. 2007. Assessing US farm drainage: Can GIS lead to better estimates of subsurface drainage extent? Washington, DC: World Research Institute.

Thorne, C. 1999. Bank processes and channel evolution in the incised rivers of North-Central Mississippi. In Incised River Channels, edited by S.E. Darby and A. Simon. John Wiley & Sons Ltd.

US Geological Survey. No date. USGS surface-water data for Minnesota. http://waterdata.usgs.gov/mn/nwis/sw

Western Regional Climate Center. No date. WRCC Climate Division monitoring products. http://www.wrcc.dri.edu/divisional.html