Nutrient Reduction Strategy

August 2020

Appendix C:
River Nutrient Trends in Minnesota

5-year Progress Report on Minnesota's Nutrient Reduction Strategy

MINNESOTA

River Nutrient Trends in Minnesota

Appendix C of the Minnesota Nutrient Reduction Strategy 5-year Progress Report

Authors and Contributors:

Lead Author - David Wall - Minnesota Pollution Control Agency (MPCA)

MPCA trends analysis and methods – James Jahnz and Lee Ganske (MPCA)

Met Council trends analysis – Hong Wang and Jack Barland (Met Council)

U.S. Geological Survey (USGS) trends analysis – Rochelle Nustad (USGS)

Review Team – the above authors, plus David Christopherson (MPCA), Judy Sventek (Met Council), and Marta Shore (University of Minnesota)

wq-s1-84f

Appendix C to the Minnesota Nutrient Reduction Strategy 5-year Progress Report

Contents

Figures

Tables

1. Introduction

Analyzing river nitrate and phosphorus trends is one of the many ways that Minnesota tracks long-term progress toward nutrient reduction goals. To gain a more complete understanding of river nutrient trends, Minnesota partner agencies assessed available data from multiple river locations over different time periods using a variety of approaches. This analysis builds upon existing and ongoing trends assessment work by the U.S. Geological Survey (USGS), Minnesota Pollution Control Agency (MPCA), and Metropolitan Council Environmental Services (Met Council).

River nutrient trends indicate how collective actions to improve the water, coupled with the influence of other external changes, are reflected in our river monitoring data. These analyses, when conducted over long periods of time, provide an understanding of the combined outcomes of land use changes, management practices, and other key factors affecting water quality. Long-term assessments are important to better distinguish between real changes in the water as opposed to temporary influences in climate and other year-to-year variability. Improvements made on the land can sometimes take decades or more before changes are observed in the ambient river water quality.

Many of the river trends assessment methods use statistical analysis techniques that largely separate the effects caused by human changes on the land from those caused by variability in precipitation and river flow. These "flow-adjusted" techniques (sometimes called "flow-corrected," "flow-normalized," or "flow-averaged") can better indicate the combined effects of best management practice (BMP) adoption and other changes made by people in the watersheds—effects that are otherwise often overshadowed by the changes in precipitation and corresponding river flows. Trends developed using flow-adjusted methods can be interpreted as changes that would occur if flow had been the same year after year.

It is possible, however, that the climate in portions of Minnesota will continue to be wetter over the long-term. For that reason, MPCA and Met Council additionally assessed nutrient load trends without adjusting for year-to-year variability in flow. The term "non flow-adjusted" in this report indicates the use of statistical techniques that do not remove the influence of year-to-year flow variability.

Each way of assessing river nutrient trends provides information about a specific aspect of the trends. A look at multiple chemical parameter concentrations and loads, different timeframes, and more than one statistical technique and model, provides a more comprehensive understanding of Minnesota's nutrient trends in rivers. The multiple combinations of trends assessments in this report make the findings more complex, but tells a more complete story.

This analysis included trends from several different timeframes. Five-year trends (since completing the 2014 Nutrient Reduction Strategy) would not generally yield meaningful conclusions about trends due to limitations in accurately assessing such short periods with statistical methods. Therefore, five-year trend analyses were not performed. This analysis focused mostly on river trends from the 10-year (recent) and 20-year (mid-range) timeframes. Analyses for *recent* timeframes represent the past 10 years, providing an indication of changes following Minnesota's Clean Water Fund establishment. Analyses for *mid-range* timeframes represent the past approximate two decades, indicating changes near the end of baseline periods established for the Mississippi and Red Rivers. For certain major rivers with lengthy monitoring records, some analysis was performed on approximately 40-year (long-term) timeframes.

To make best use of previous and ongoing efforts to statistically assess river nutrient trends, the work of three different organizations contributed to this analysis as follows:

- **USGS**: Red River Basin mid-range trends
- **Met Council**: Major rivers entering and leaving the Twin Cities Metropolitan area (mid-range and long-term trends), based on recent updates to the work reported in Metropolitan Council (2018). Met Council updated their work reported in www.metrocouncil.org/river-assessment to also include the years 2016-2018 and new river nutrient load trend analyses
- **MPCA**: In-depth analysis of certain major rivers with long-term monitoring results, along with a more streamlined analysis of all other rivers monitored by the MPCA for at least the past ten years (recent, mid-range and long-term trends)

The availability and duration of monitoring data influenced the selection of sites for this report, as did the emphasis on larger rivers. Trends were determined for flow-adjusted and non flow-adjusted concentrations and loads, highlighting both nitrite+nitrate-N (referred to often as "nitrate" or "NOx") and total phosphorus (referred to often as "phosphorus" or "TP").

The difference between concentration and load is worth noting. Concentrations are direct measures of water quality that define such things as the probability of algae blooms, the health of the water for fish and other aquatic life, and the suitability for drinking. Loads describe the amount of nutrients moving downstream over a period of time and are affected by watershed conditions, weather, and climate. Loads are a combination of concentrations and river flow.

This analysis includes an evaluation of both concentration and load trends for major river sites near state borders or confluences with other major rivers. For most HUC-8 watershed outlets and secondary sites, the analyses evaluated only concentration trends. The statistical methods and timeframes selected for assessment varied by the organization conducting the analysis, data availability, and the relative importance of the river to downstream waters (Table 1).

A description of the methods, as well as additional site and sampling details for the Met Council analyses can be found in Met Council (2018) www.metrocouncil.org/river-assessment. The methods described in Met Council (2018) are the same as used for the QWTREND analyses in this report, with the exception of an expanded timeframe for the years 2016-2018 included in this report.The USGS analysis methods are described in Nustad and Vecchia (2020) with further details about the use of R-QWTREND at https://pubs.er.usgs.gov/publication/ofr20201014. MPCA methods are included as Attachment A to this report.

Unless otherwise noted, a 90% statistical confidence ($p<0.1$) denotes a statistically significant trend. A trend described as *not significant* or *non-significant* can mean there is no trend, but these terms can also mean that the data set was not conducive to demonstrating a significant change. In some cases, there are not enough data or enough years to have high confidence in a real change given the year-to-year variability. For that reason, the analyses show a particularly high number of non-significant trends when assessing the recent time period (i.e., 10 years).

Table 1. Metadata for river nutrient concentration and load trend data used in this report.

Flow Statistical Method	Concentration Trends Metadata	Load Trends Metadata
Flow-adjusted	**Region:** Red River Valley **Organization:** USGS **Timeframe:** 2000-2015 (incorporating additional years between 1995-2017 as data were available) **Method:** **R-**QWTREND **Region:** Twin Cities Metro **Organization:** Met Council **Timeframe(s):** approximately 20- and 40-year periods ending in 2018 **Method:** QWTREND **Region:** Statewide **Organization:** MPCA **Timeframe(s):** approximately 10-, 20- and 40-year periods ending in 2017-18 **Methods:** Bootstrapped seasonal Kendall w/flow adjustment; QWTREND for Mississippi River Winona and St. Louis River Scanlon	**Region:** Mississippi River at Winona and Red Wing, St. Louis River at Scanlon, **Organization:** MPCA **Timeframe(s):** 36-, 43- and 20-year periods ending in 2017-18 **Method**: EGRETci WRTDS
Not-flow-adjusted	**Region:** Statewide **Organization(s):** MPCA **Timeframe(s):** 10-, 20-, 40-year periods ending in 2017 **Method:** Bootstrapped Seasonal Kendall	**Region:** Metro Area Major Rivers **Organization:** Met Council **Timeframe(s):** 43 years ending in 2018 **Method:** Mann Kendall on annual loads calculated with FLUX32

Trend results for phosphorus and nitrate are presented separately due to differences between the nutrients related to sources, transport pathways from source to river, and practices to reduce sources. For nitrogen, the analysis focuses on nitrate results rather than total nitrogen, since nitrate is the most dominant form of nitrogen in most polluted waters and it has important environmental and human health effects. Total nitrogen trends were assessed at most of the same sites and had similar trend directions, with only a few exceptions which are noted.

2. Phosphorus Results

The analysis for phosphorus begins with a statewide MPCA assessment using a less labor-intensive statistical approach, followed by the more in-depth analyses at certain key river monitoring sites in the (1) Mississippi River Basin, (2) Red River Basin, and (3) Lake Superior Basin.

2.1 Statewide Phosphorus (MPCA)

Statewide phosphorus concentration trends include data from MPCA monitoring sites assessed using the bootstrapped seasonal Kendall approach for three different timeframes Additionally, 20-year mid-range trend analyses were conducted by MPCA, Met Council and USGS using WRTDS EGRETci, QWTREND and R-QWTREND, respectively, at select monitoring sites across Minnesota.

2.1.1 All MPCA Sites - Seasonal Kendall Test

Using the bootstrapped seasonal Kendall approach at MPCA-monitored sites statewide, phosphorus concentrations have generally either decreased or had no statistically significant trend during recent decades (Figure 1). When adjusting for flow variability, no sites had an increasing concentration trend. Even when not adjusting for flow, only one site out of 50 was found to have increasing phosphorus concentrations over the past 10- and 20-year periods.

Using the flow-corrected seasonal-Kendall test, over half of the sites had non-significant 10-year phosphorus concentration trends ($p<0.1$). The fraction of non-significant trends decreased as the length of monitoring period increased, such that 11 of 13 sites had significant 20-year trends and all of the 10 sites evaluated for 40-year records had significant trends.

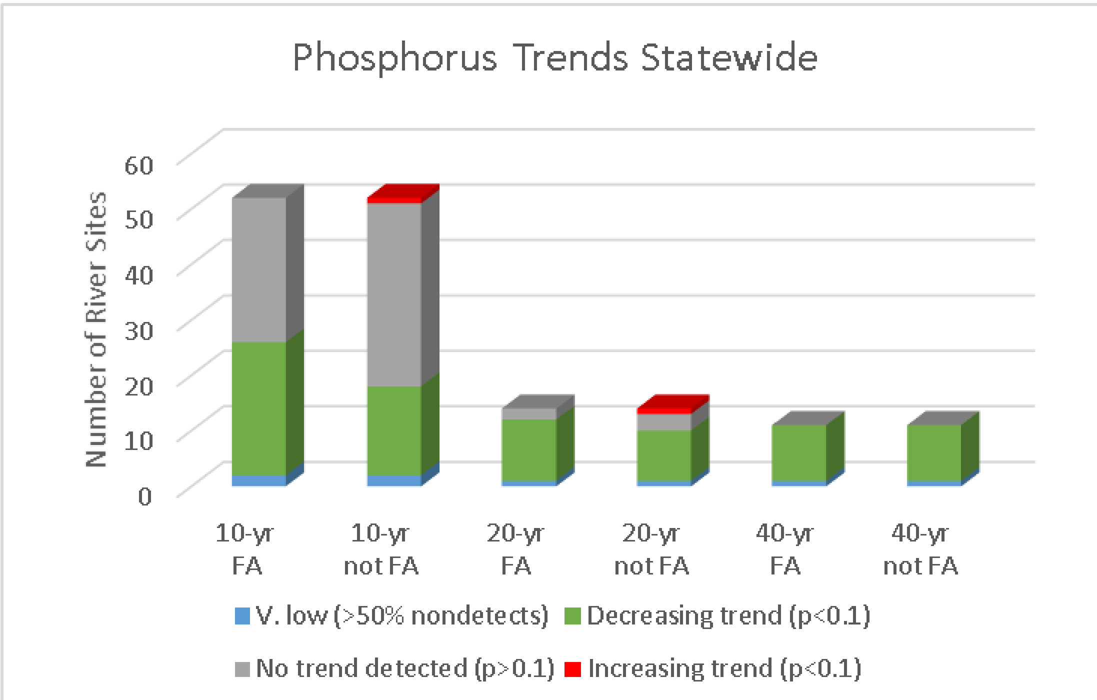

Figure 1. Bootstrapped Seasonal Kendall phosphorus concentration trend results using both flow-adjusted (FA) and non flow-adjusted (not FA) techniques at MPCA-monitored river sites across the state.

The majority of the 10-year decreasing phosphorus concentration trends were found in the eastern part of the state, with the western and northwestern parts of the state showing largely no detectable trends (Figure 2). Through this analysis, the only area of the state with non-significant phosphorus concentration trends over the past 20 years is in the upstream stretches of the Minnesota River Basin (Figure 3).

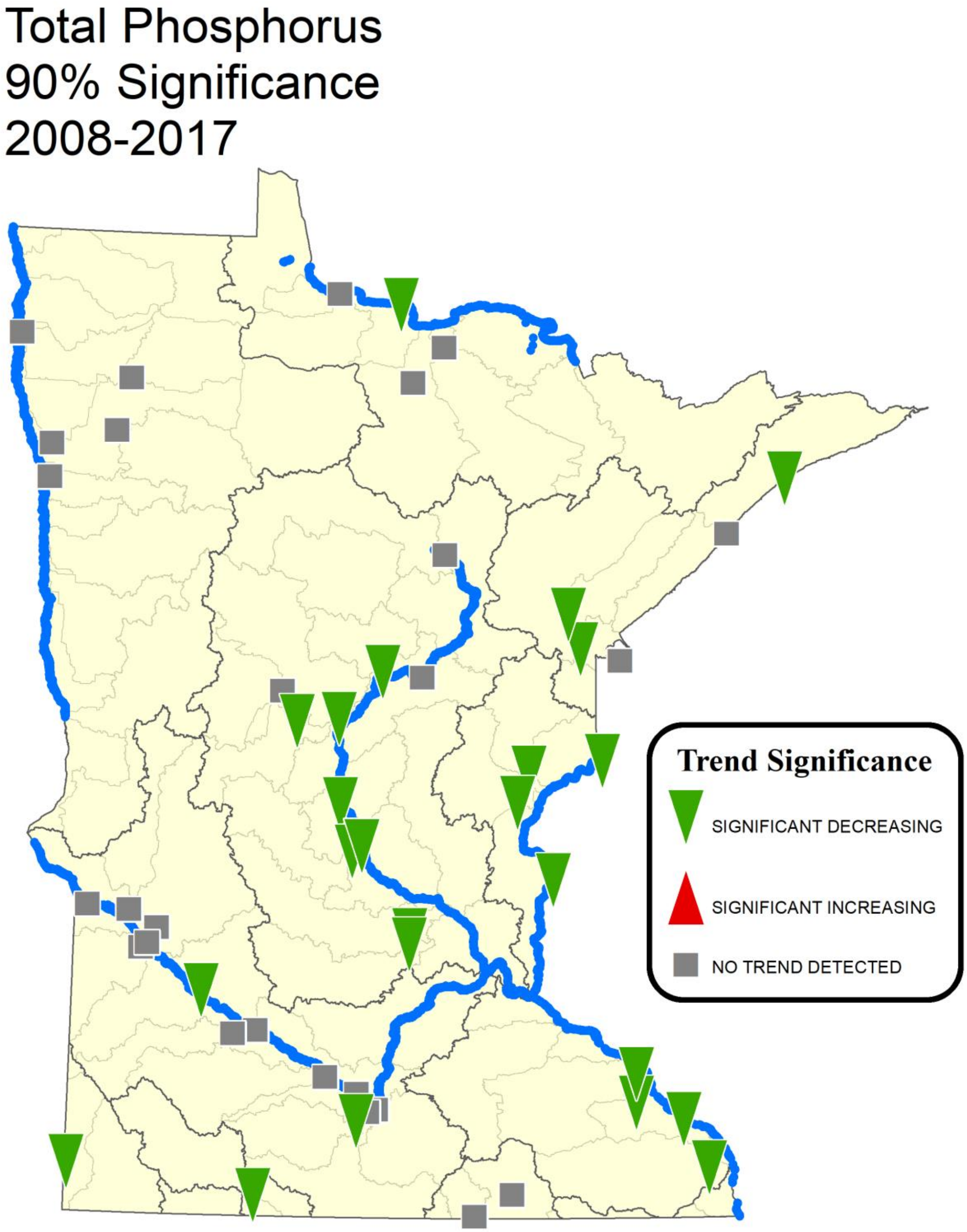

Figure 2. Recent (2008-17) phosphorus trends at MPCA sites assessed using a flow-adjusted bootstrapped Seasonal Kendall method.

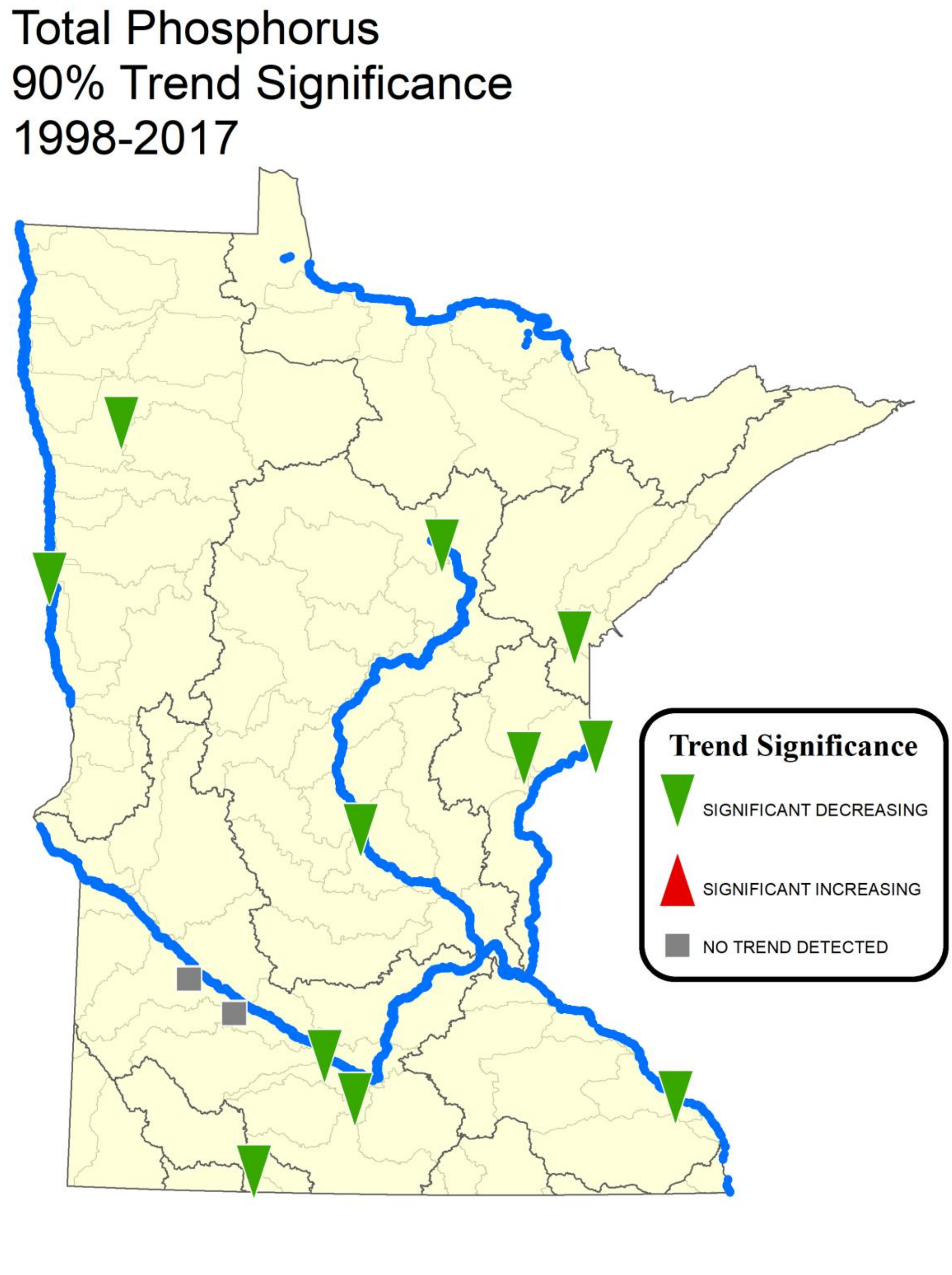

Figure 3. Mid-range (1998-2017) phosphorus trends at MPCA sites assessed using a flow-adjusted Seasonal Kendall approach.

2.1.2 Statewide Mid-range Phosphorus Trends from Met Council, USGS, and MPCA

Rigorous statistical analysis techniques using QWTREND and R-QWTREND (concentration) and/or WRTDS EGRETci (loads) were performed at major river sites and certain other tributaries to major rivers, as described below. Associated site locations and the organizations conducting trends analyses are shown in Figure 4.

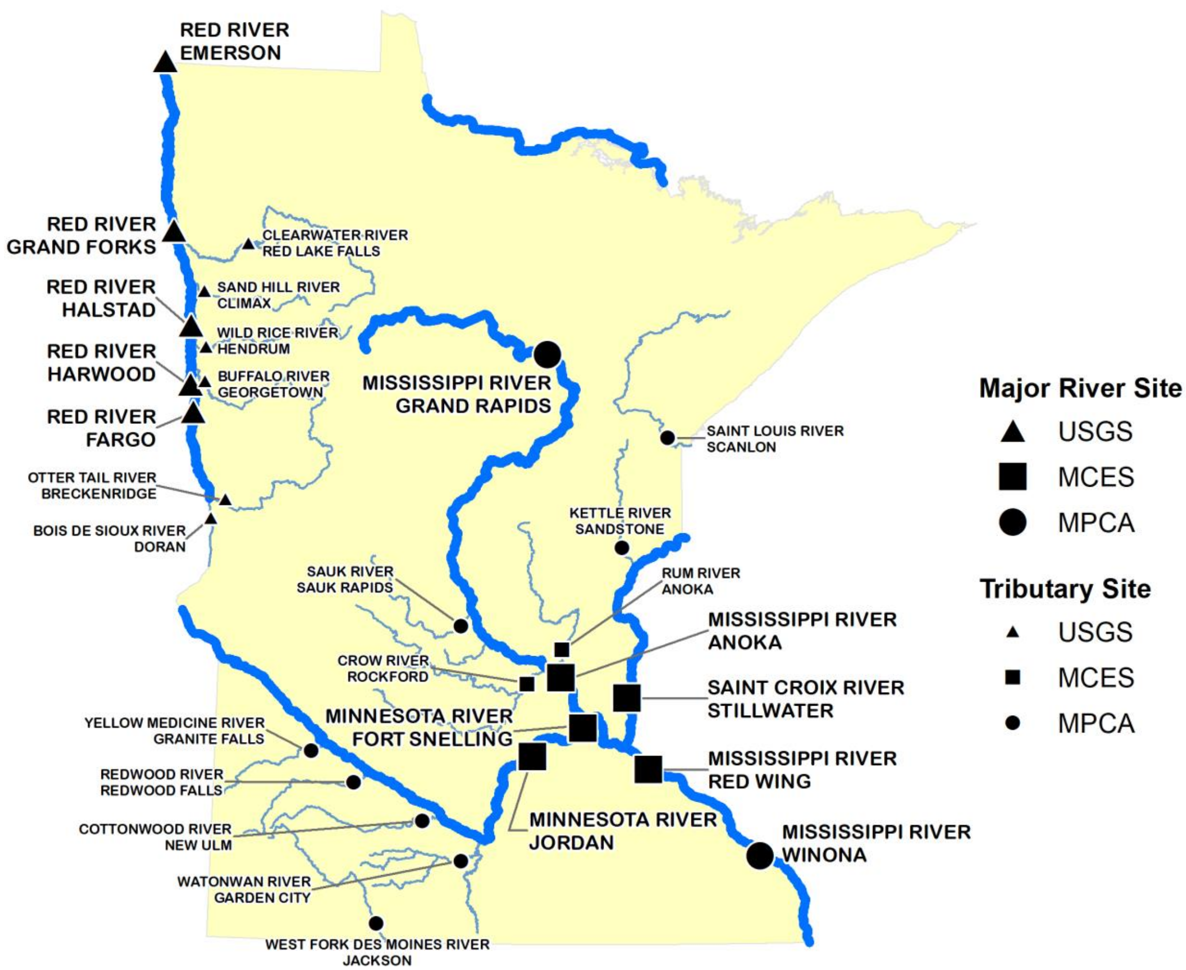

Figure 4. River monitoring site locations for major river and tributary sites where trends were evaluated for about the past two decades.

Mid-range (approximately 20-year) flow-adjusted phosphorus concentration trends were conducted using QWTREND and R-QWTREND (Red River Basin) at major river sites around the state (Figure 5). QWTREND and R-QWTREND was used to assess trends at all mapped sites, except that the flow-adjusted Seasonal Kendall test was used at tributaries to the Minnesota River, along with the Sauk River and Kettle River.

A majority of the sites (21 of 28) show decreasing phosphorus concentration trends. Six of the 28 sites had no significant trend detected. Only the Red River at the Emerson site had an increasing trend. The

Emerson site is a point on the Red River that has upstream nutrient additions from North Dakota and Manitoba, in addition to Minnesota's contributions.

In general, phosphorus concentration trend directions for mid-range trends in figure 5 are generally similar to the mid-range trends in figure 3.   However, figure 5 also includes additional sites assessed by Met Council and the USGS. The method of statistical trend analysis is also different for most of the sites on figure 5 as compared to figure 3, as previously described.

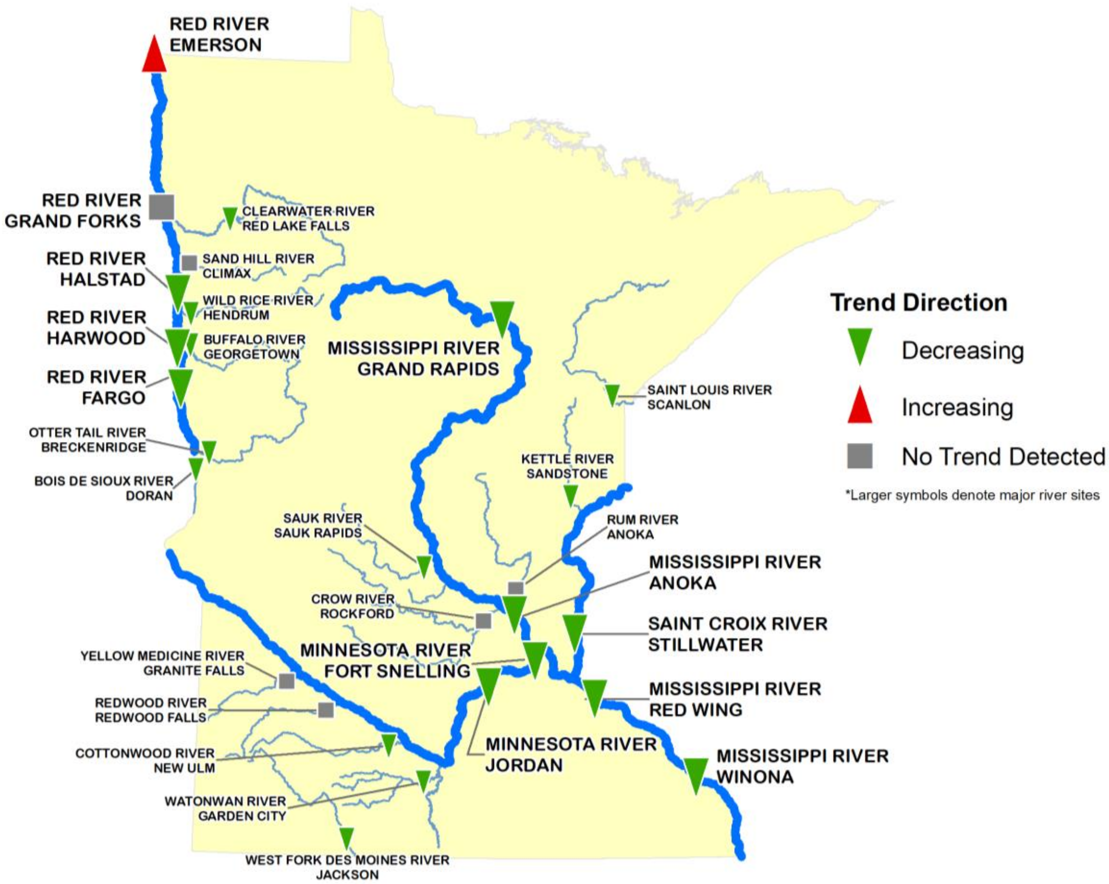

Figure 5. River monitoring site locations at sites with enough information to determine mid-range (approximately 20-year) flow-adjusted phosphorus concentration trends. Large symbols represent major river sites and small symbols represent tributary river sites.

More details about phosphorus concentration trend results are described below for sites where the QWTREND and R-QWTREND methods were used.

2.2 Mississippi River Basin

An overview of phosphorus trends in the Mississippi River and its major tributaries is shown in Table 2. Trends over the past approximate 20 and 40 years consistently show decreasing flow-adjusted concentration trends in the range of 15-53%.

At the two Mississippi River sites evaluated for load trends (Red Wing and Winona), flow-adjusted loads also show decreases. The magnitude of these decreasing flow-adjusted phosphorus loads range from 37% in Red Wing to 54% at Winona.

A more simplified Mann Kendall analysis of annual loads (not flow-adjusted) shows non-significant trends (p<0.1 is our criteria for statistical significance) at all evaluated sites. Increasing precipitation during the past 20 years is likely one important reason that the loads, when assessed without any flow adjustment, show a non-significant trend as compared to the significant decreases in flow-adjusted loads. The calculated p-value for each non-significant load trend analysis is included in Table 2. The 20-year non flow-adjusted load trends in the Minnesota River had p-values just over 0.1 and, therefore, were close to being statistically significant. More detailed results and analysis for each site are described below.

Table 2. Overview of Mississippi River Basin phosphorus trend results for both concentration and load at long-term major river monitoring sites.

A decreasing trend is denoted by "-." Non-significant trends (p<0.1) is denoted by "NS." P-value indicates the significance level of trends that are not statistically significant.

Monitoring site	Parameter and method (phosphorus)	Recent (~ 10 yr)	Mid-range (~ 20 yr)	Long-Term (~ 40 yr)
Mississippi River Winona	Concentration (QWTREND flow-adjusted)	**-41%**	**-50%**	**-53%**
	Load flow-adjusted (EGRETci WRTDS-WRTDS)	**-50%**	**-54%**	**-52%**
Mississippi River Red Wing	Concentration (QWTREND flow-adjusted)		**-21%**	**-40%**
	Load flow-adjusted (EGRETci WRTDS-WRTDS)	**-27%**	**-37%**	**-36%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.36	**NS** P=0.67
Mississippi River Anoka	Concentration (QWTREND flow-adjusted)		**-26%**	**-41%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.87	**NS** P=0.14
Minnesota River Jordan	Concentration (QWTREND flow-adjusted)	**See narrative**	**-17%**	**-30%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.11	**NS** P=0.48
Minnesota River Fort Snelling	Concentration (QWTREND flow-adjusted)		**-18%**	**-51%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.18	**NS** P=0.92
St. Croix River Stillwater	Concentration (QWTREND flow-adjusted)		**-15%**	**-27%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.77	**NS** P=0.58

In addition to the results in Table 2, Met Council used the QWTREND analysis to assess phosphorus trends in the Crow River, a major tributary delivering nutrients in the Upper Mississippi River Basin. The Crow River at Rockford did not have statistically significant phosphorus concentration trends from 1999-2018. The MPCA assessed trends on many other HUC-8 tributaries in the Mississippi Basin using the Seasonal Kendall method, as previously discussed.

2.2.1 Mississippi River at Winona - Phosphorus

The Mississippi River at Winona site provides short- and long-term monitoring records enabling statistical analysis of trends near the state border with Iowa. While this site includes some flow from Wisconsin rivers, it is mostly influenced by waters flowing from the Minnesota River, Upper Mississippi River, St. Croix River, along with the Zumbro and Cannon Rivers (Figure 6). Therefore, this site represents an integrated sample of much of the nutrient pollution that ultimately leaves the state via the Mississippi River.

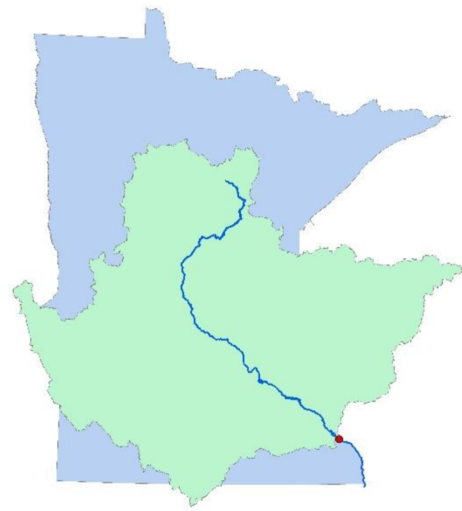

Figure 6. Watershed draining to Mississippi River at Winona monitoring site.

It should be noted that Winona phosphorus concentration data set has a data gap in the middle of the record between 1994 and 2000. The models estimate loads based on river flows and the river flow and concentration relationships. While the long-term and short-term trends are less affected by this gap, the mid-range period is more greatly influenced.

Using the QWTREND model, the MPCA assessed flow-adjusted phosphorus concentration trends over three time periods, representing the past 11 (2007-2017), 21 (1997-2017) and 36 years (1982-2017). For all three periods, the phosphorus concentration decreased by approximately 50% (Table 2).

The MPCA used EGRETci WRTDS to evaluate the flow-adjusted phosphorus load trends for the short-term (2008-2018), mid-range (2001-2018) and long-term (1982-2018) timeframes. All three periods showed major load reductions of a similar magnitude (2.7 to 2.9 million pounds per year). Based on the graph of modeled load (flux) trends (Figure 7), it appears that flow-adjusted phosphorus loads were increasing during the 1980s and then shifted to a decreasing trend in the early 1990s.

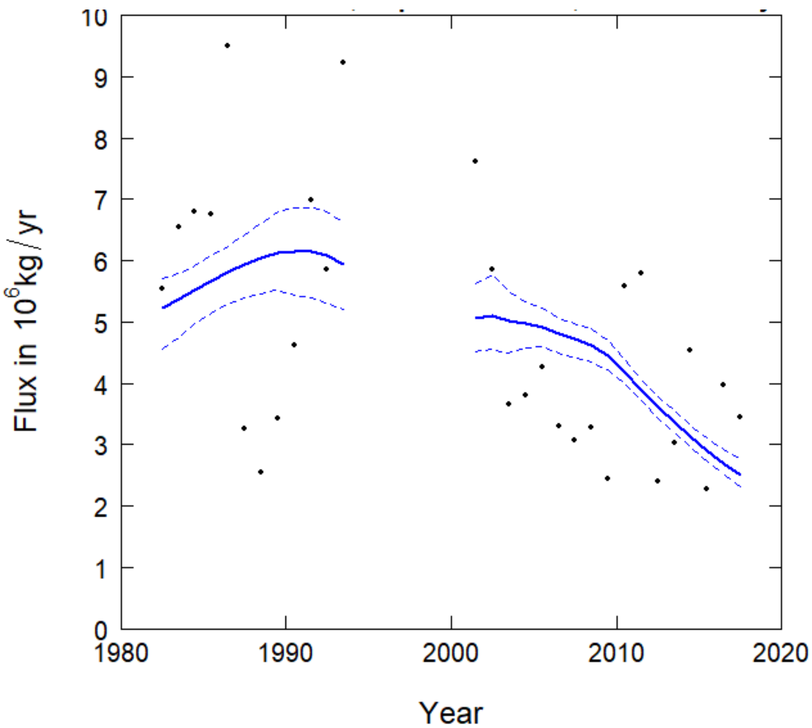

Figure 7. Flow-adjusted phosphorus load trends modeled with EGRETci WRTDS at the Mississippi River Winona site.

The non flow-adjusted total phosphorus loads (Figure 8) show a decreasing trend, but suggest no trend between 2003 and 2017. River flow greatly affects the view of non flow-adjusted loads. It appears that precipitation increases in the recent years have increased flow and offset much of the progress made with flow-adjusted phosphorus concentrations.

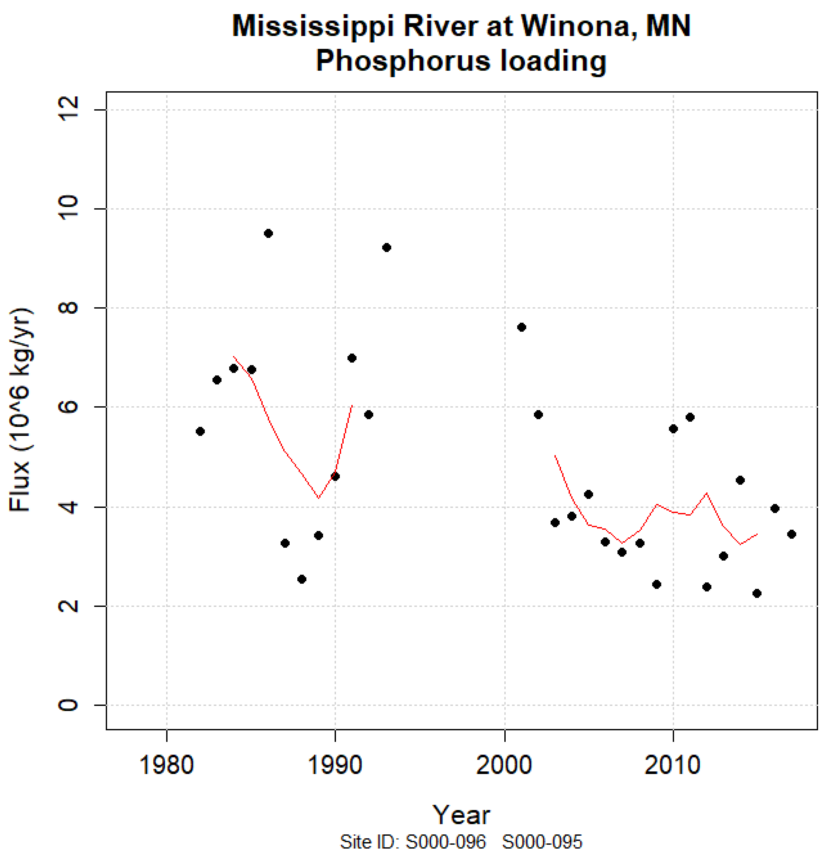

Figure 8. Mississippi River at Winona five-year rolling average loads (non flow-adjusted). Loads calculated with EGRETci WRTDS.

2.2.2 Mississippi River at Red Wing (Lock and Dam #3) Phosphorus

The Red Wing site (also known as Lock and Dam #3) in Minnesota is an important long-term continuously monitored site for evaluating nutrient reduction progress throughout much of the state. The location is downstream of the Upper Mississippi River Basin, the Minnesota River Basin, the St. Croix River Basin, and the Twin Cities Metropolitan area (Figure 9). The portion of nutrients at this site that do not leave the state are either temporarily or permanently lost from the river in the downstream Lake Pepin and Mississippi River backwaters.

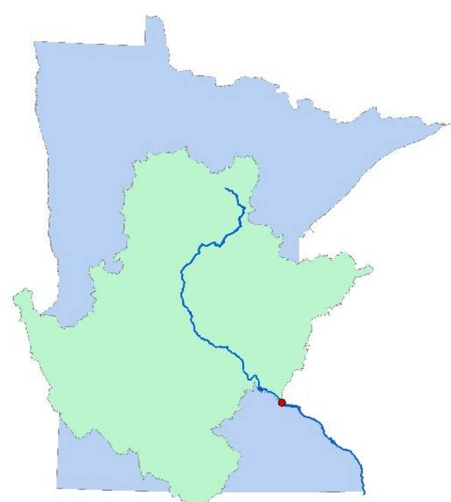

Figure 9. Watershed draining to Mississippi River at Red Wing monitoring site.

The Met Council analysis using the QWTREND program showed flow-adjusted phosphorus concentration reductions of 21% and 40% over the past 20 and 40 years, respectively. Phosphorus concentration trends were best represented by a one-trend model (Table 3 and Figure 10), showing that TP concentrations decreased gradually over the entire assessment period (1976 to 2018).

Table 3. Statistical Trend for TP Concentration in the Mississippi River at Lock and Dam 3.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 2018	0.17 – 0.10	-41%	-0.0016	< 0.0001	⬇
Overall Trends					
20 years (1999 – 2018)	0.12 – 0.10	-21%	-0.0013	–	⬇
40 years (1979 – 2018)	0.17 – 0.10	-40%	-0.0017	–	⬇

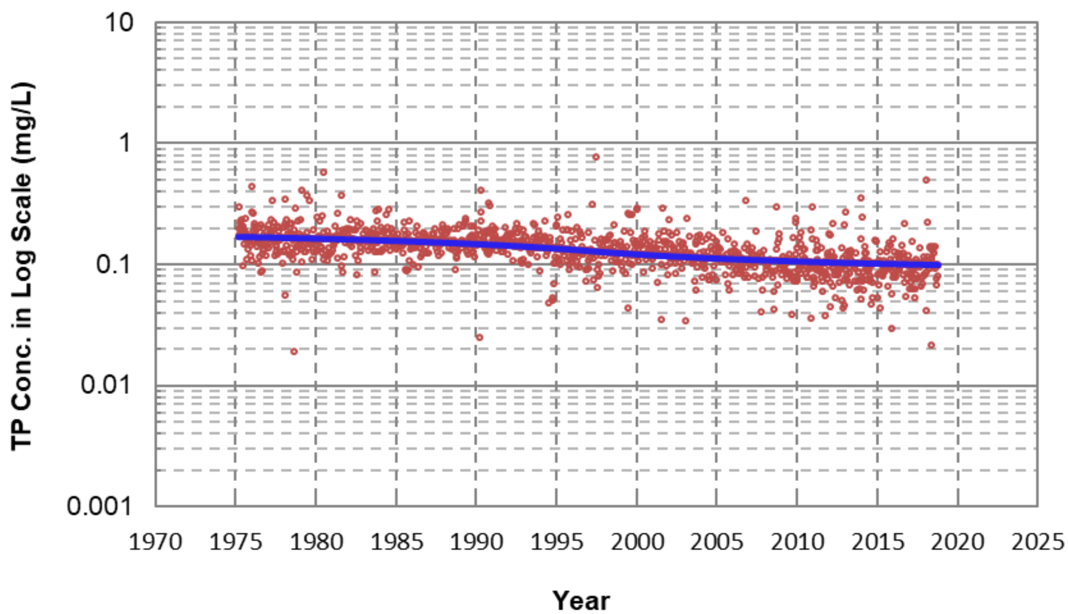

Figure 10. Statistical Trend for Flow-Adjusted TP Concentration in the Mississippi River at Lock and Dam 3.

Annual phosphorus loads at Red Wing show a very high year-to-year variability (Figure 11). While the five-year rolling average shows a general load decrease from 1994-2008, a separate analysis of load trends (non flow-adjusted) did not show a significant change for either mid-range or long-term periods. The lack of certainty about a trend is likely attributed to increased average and maximum flow in the river over the past 20 years (Table 4 and Figure 12). While the water has lower flow-adjusted phosphorus concentrations, there is more water flowing in the river and thus more delivery of nonpoint source phosphorus. The net effect is no significant trend in phosphorus load.

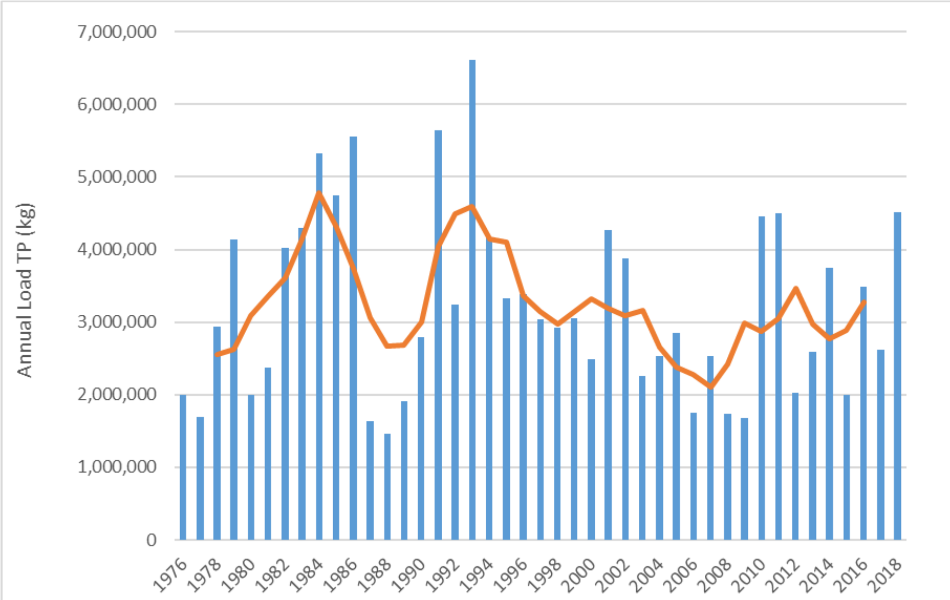

Figure 11. Annual phosphorus Loads (Non Flow-Adjusted) in the Mississippi River at Red Wing (Lock and Dam 3) and five-year rolling average load (orange).

Table 4. Statistical Trends for River Flow Volume in the Mississippi River at Lock and Dam 3 near Red Wing. "No trend" means no trend detected with the trend analysis methods.

Trend Period		**Change Rate (CFS)**	**Change Rate (%)**	***p***	**Trend**
20 years (1999 – 2018)	Minimum	–	–	0.12	No trend
	Average	479	40%	0.03	⬆
	Maximum	1,560	38%	0.07	⬆
40 years (1979 – 2018)	Minimum	–	–	0.58	No trend
	Average	–	–	0.20	No trend
	Maximum	–	–	0.23	No trend

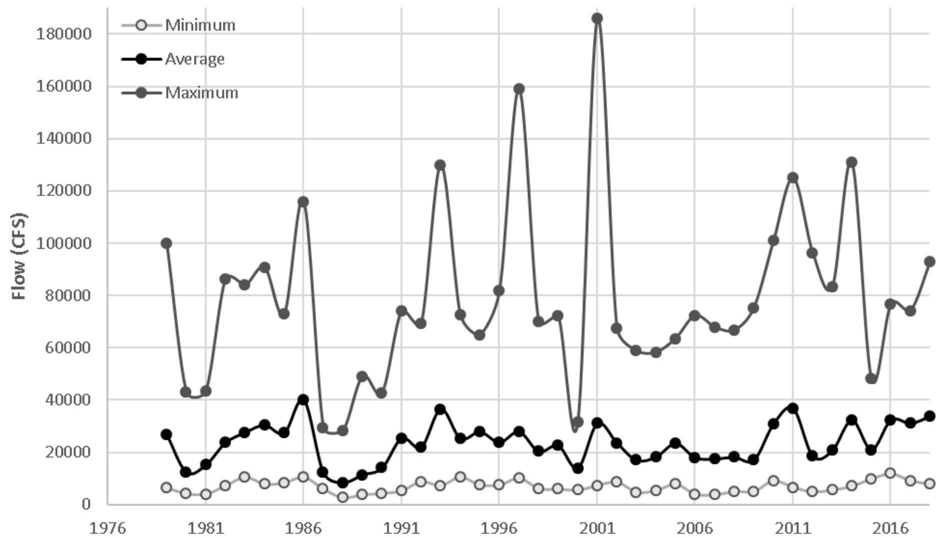

Figure 12. Annual minimum, maximum, and average daily flow in the Mississippi River at Lock and Dam 3 near Red Wing (1979-2018).

In a separate analysis of the data, the MPCA evaluated flow-adjusted loads at Red Wing using EGRETci WRTDS. Significant downward phosphorus loading trends were found for 12-year (2007-2018), 22-year (1997 to 2018) and 42-year (1977-2018) timeframes, resulting in an estimated phosphorus decrease of 0.87 million pounds (27% reduction), 1.3 million pounds (37% reduction), and 1.4 million pounds (36% reduction) over those three periods, respectively.

2.2.3 Mississippi River at Anoka – Phosphorus

The Mississippi River at Anoka site represents flow coming from areas mostly to the north and upstream of the Twin Cities (Figure 13). This part of the river has much lower nutrient concentrations than downstream of the confluence with the Minnesota River. The Met Council analysis using the QWTREND program shows flow-adjusted total phosphorus concentration reductions of 26% and 41% over the past 20 and 40 years, respectively, in the Mississippi River at Anoka. The decreases were particularly rapid during the 2006 to 2018 period (Table 5 and Figure 14).

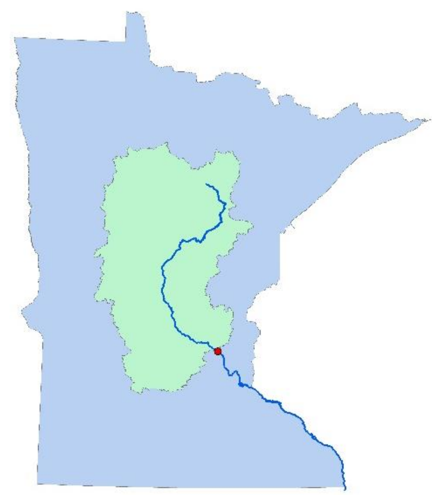

Figure 13. Watershed draining to Mississippi River at Anoka monitoring site.

Table 5. Statistical Trends for TP Concentration in the Mississippi River at Anoka.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 2005	0.10 – 0.08	-26%	-0.00089	< 0.0001	↓
2006 – 2018	0.08 – 0.06	-22%	-0.0013	0.0004	↓
Overall Trends					
20 years (1999 – 2018)	0.08 – 0.06	-26%	-0.0010	–	↓
40 years (1979 – 2018)	0.10 – 0.06	-41%	-0.0010	–	↓

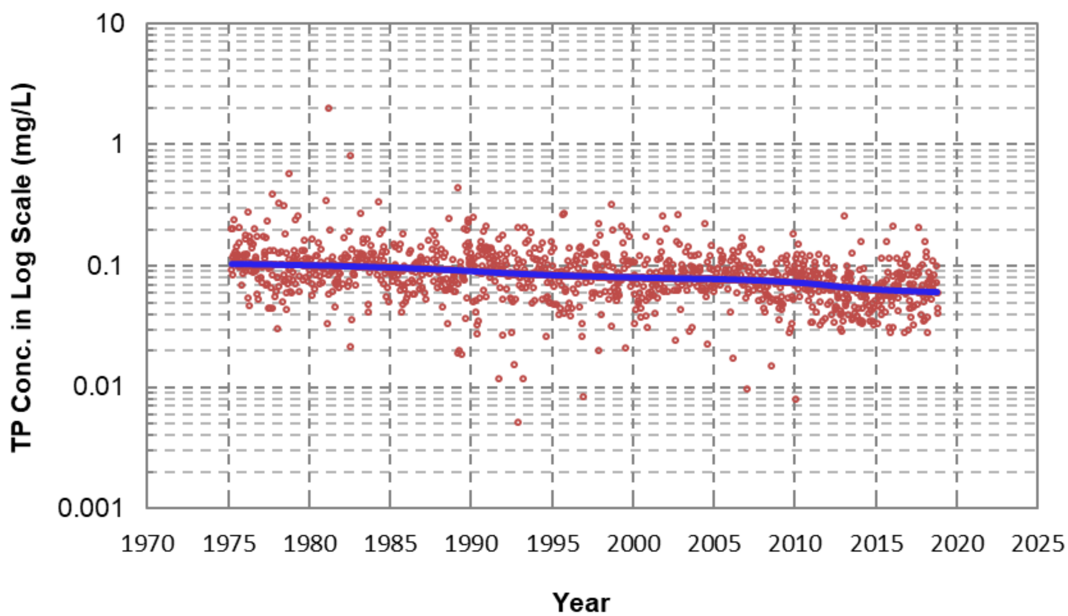

Figure 14. Statistical Trends for Flow-Adjusted TP Concentration in the Mississippi River at Anoka.

A separate analysis of non flow-adjusted load trends did not show a significant change for either time period. Trends in river flow at this site were mostly non-significant, except that low-flow conditions were significantly increasing over the past 20 years. Flow variability may be one factor affecting the lack of significance in the non flow-adjusted load trends (Table 6 and Figure 15).

Table 6. Statistical Trends for TP Loads in the Mississippi River at Anoka (not flow-adjusted). "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.87	No trend
40 years (1979 – 2018)	–	–	0.14	No trend

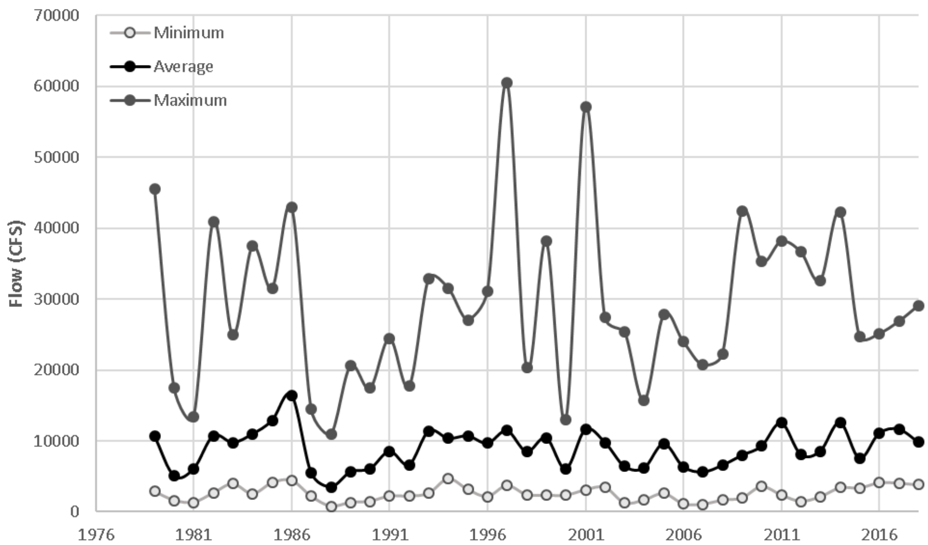

Figure 15. Annual minimum, maximum, and average daily flow in the Mississippi River at Anoka (1979-2018).

2.2.4 Minnesota River, Jordan – Phosphorus

The Minnesota River at Jordan is one of two long-term sites on the Minnesota River monitored by Met Council, with the other located near the mouth of the river at Fort Snelling (Figure 16 and Figure 20). The Jordan location receives over 90% of the same flow that pours into the Mississippi River site near Fort Snelling, where high amounts of nitrogen and phosphorus enter the Mississippi River.

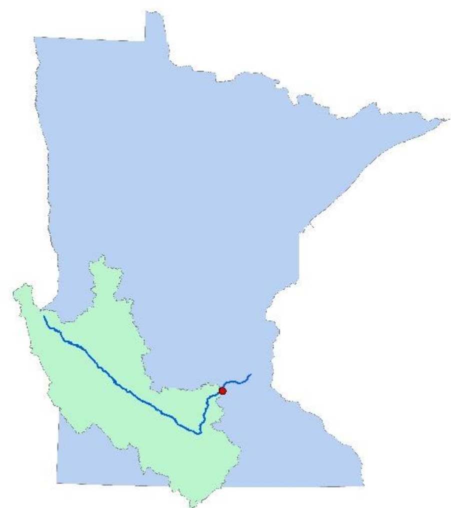

Figure 16. Watershed draining to Minnesota River at Jordan monitoring site.

The Met Council analysis with QWTREND showed three different periods of change over the course of the assessment period from 1979 to 2018 (Table 7 and Figure 17). The trend results show that TP concentration decreased slowly from 1979 to 2005, followed by a quick drop from 2005 to 2008, then increased slightly over the next 10 years from 2009 to 2018.

Overall, TP concentrations decreased by 17 and 30%, respectively, during the past 20 years (1999 to 2018) and 40 years (1979 to 2018), indicating an overall long-term improvement in flow-adjusted phosphorus concentrations. However, it appears that these long-term trends may be reversing as indicated by the significant increase from 2009-2018. Additional years of monitoring will provide the information necessary to evaluate if the more recent increasing trends continue.

Table 7. Statistical Trends for flow-adjusted TP Concentration in the Minnesota River at Jordan.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1979 – 2004	0.23 – 0.19	-18%	-0.0016	0.0001	⬇
2005 – 2008	0.19 – 0.14	-25%	-0.012	< 0.0001	⬇
2009 – 2018	0.14 – 0.16	14%	0.0020	0.04	⬆
Overall Trends					
20 years (1999 – 2018)	0.19 – 0.16	-17%	-0.0017	–	⬇
40 years (1979 – 2018)	0.23 – 0.16	-30%	-0.0017	–	⬇

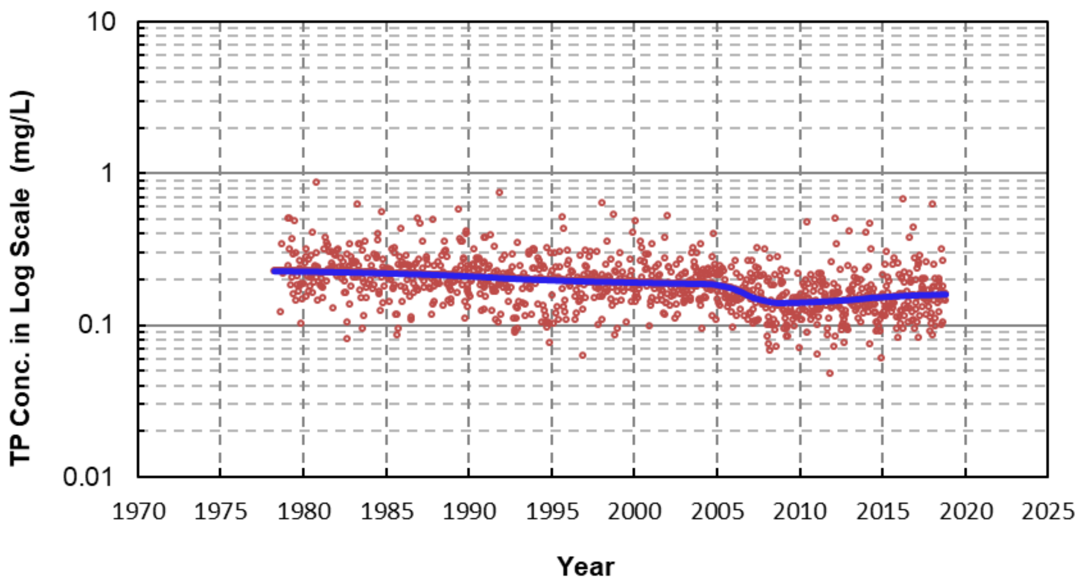

Figure 17. Statistical Trends for Flow-Adjusted TP Concentration in the Minnesota River at Jordan.

Phosphorus loads at Jordan show that the five-year rolling average has generally increased since about 2004 (Figure 18). Using a non flow-adjusted approach, Met Council did not find a statistically significant phosphorus load trend for the past 20 and 40 years (Table 8). While the non flow-adjusted load trend has increased during the past 20 years, the increase has been just over the threshold for considering it a statistically significant trend (p=0.11). A 68% increase in average river flow volume at this site during the past 20 years has increased phosphorus loads, even though flow-adjusted concentrations have been decreasing during the same timeframe (Table 9 and Figure 19).

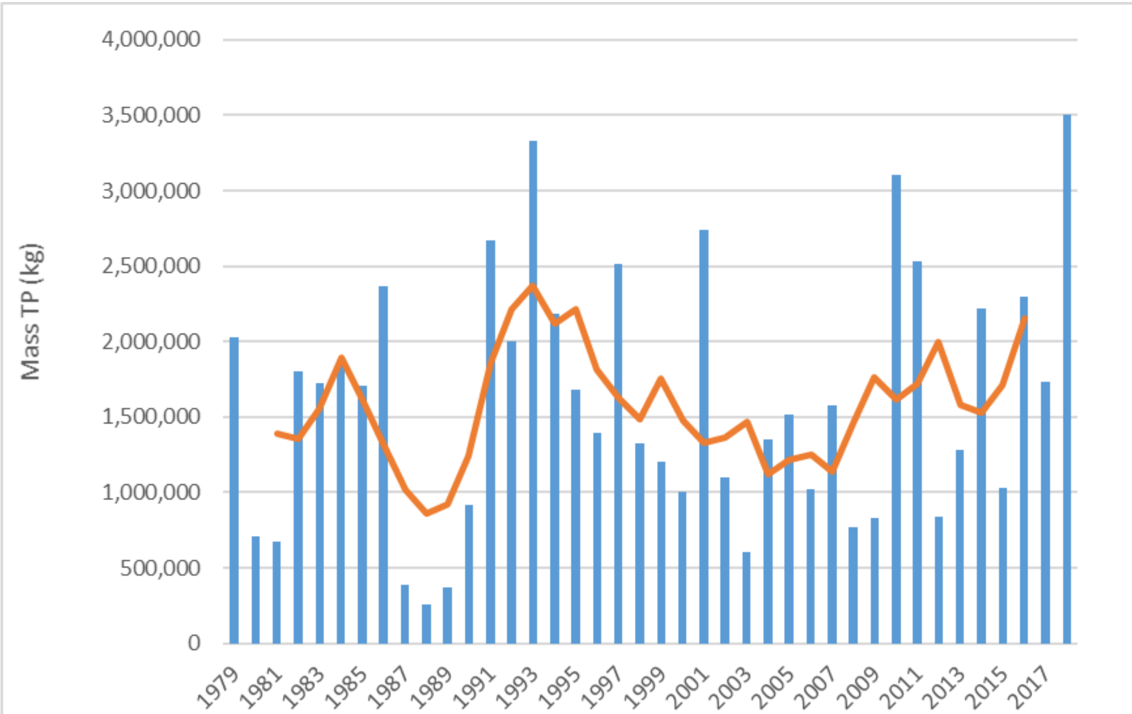

Figure 18. Annual TP Loads (non flow-adjusted) in the Minnesota River at Jordan (1979-2018), also showing the 5-year moving average (orange line).

Table 8. Statistical Trends for Non Flow-Adjusted TP Loads in the Minnesota River at Jordan. "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.11	No trend
40 years (1979 – 2018)	–	–	0.48	No trend

Table 9. Statistical Trends for River Flow Volume in the Minnesota River at Jordan. "No trend" means no trend detected with the trend analysis methods.

Trend Period		Change Rate (CFS)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	Minimum	27.7	61%	0.10	↑
	Average	247	68%	0.06	↑
	Maximum	–	–	0.21	No trend
40 years (1979 – 2018)	Minimum	–	–	0.23	No trend
	Average	–	–	0.17	No trend
	Maximum	–	–	0.11	No trend

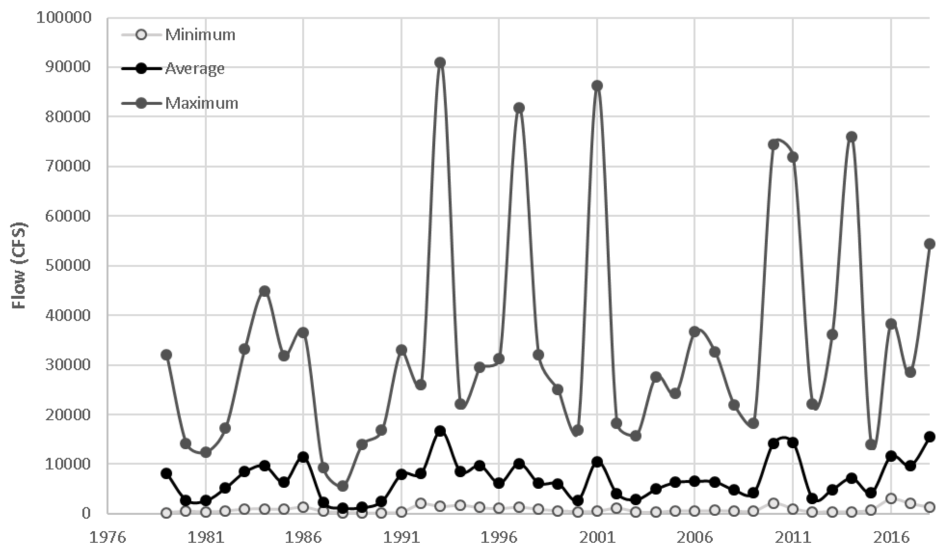

Figure 19. Annual minimum, maximum, and average daily flow in the Minnesota River at Jordan (1979-2018).

2.2.5 Minnesota River, Fort Snelling – Phosphorus

The Fort Snelling location on the Minnesota River is immediately upstream of the river mouth and its confluence with the Mississippi River (Figure 20). The QWTREND analysis showed a phosphorus concentration decrease from 1976 to 2000, followed by a more gradual decrease from 2001 to 2018. Overall, TP concentrations decreased by 18 and 51%, during the past 20 and 40 years, respectively (Table 10 and Figure 21).

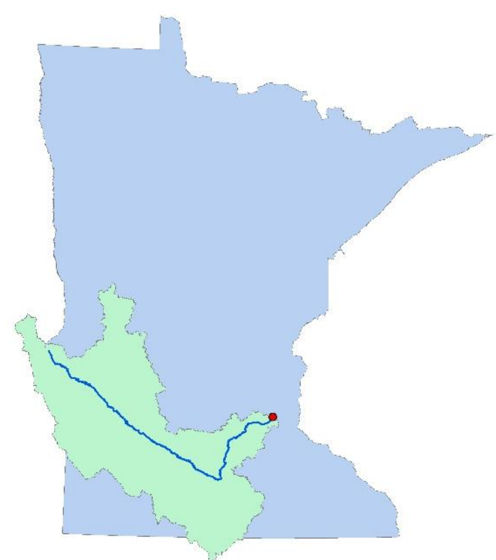

Figure 20. Minnesota River at Fort Snelling drainage area.

Table 10. Statistical Trends for TP Concentration in the Minnesota River at Fort Snelling.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 2000	0.33 – 0.19	-44%	-0.0057	< 0.0001	⬇
2001 – 2018	0.19 – 0.16	-16%	-0.0017	0.005	⬇
Overall Trends					
20 years (1999 – 2018)	0.19 – 0.16	-18%	-0.0018	–	⬇
40 years (1979 – 2018)	0.32 – 0.16	-51%	-0.0040	–	⬇

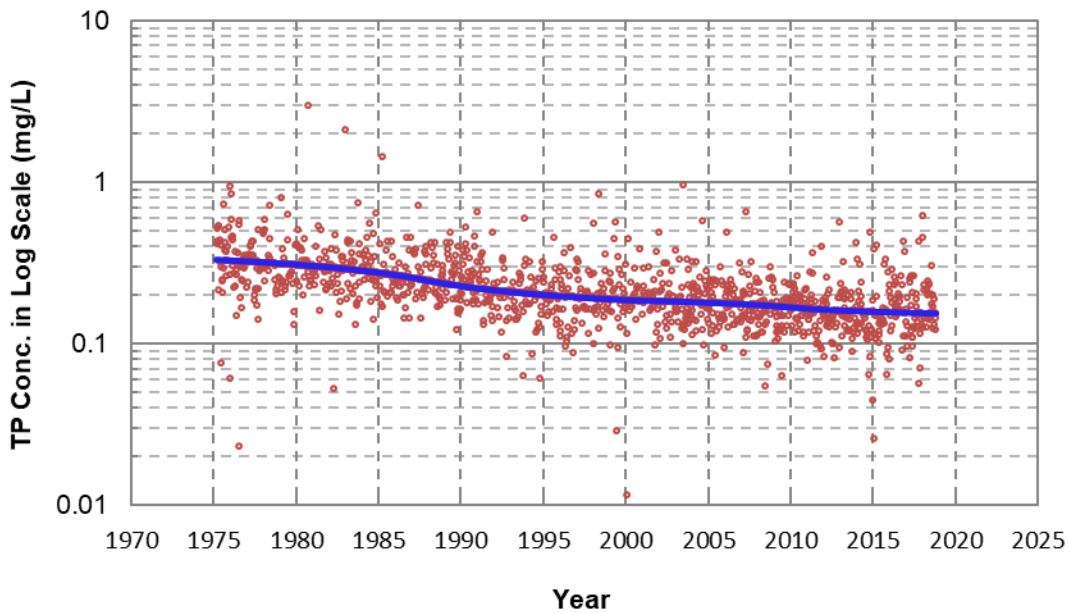

Figure 21. Statistical Trends for Flow-Adjusted TP Concentration in the Minnesota River at Fort Snelling.

Met Council did not find a statistically significant phosphorus load trend (non flow-adjusted) for the past 20 and 40 years (Table 11) at Fort Snelling. A 75% increase in flow during the past 20 years is a factor explaining why phosphorus concentrations have dropped in the past 20 years, but loads have not correspondingly decreased (Table 12).

Table 11. Statistical Trends for Non Flow-Adjusted TP Loads in the Minnesota River at Fort Snelling. "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.18	No trend
40 years (1979 – 2018)	–	–	0.92	No trend

Table 12. Statistical Trends for River Flow Volume in the Minnesota River at Fort Snelling. "No trend" means no trend detected with the trend analysis methods.

Trend Period		Change Rate (CFS)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	Minimum	65.0	118%	0.01	⬆
	Average	285	75%	0.05	⬆
	Maximum	–	–	0.23	No trend
40 years (1979 – 2018)	Minimum	16.1	64%	0.04	⬆
	Average	–	–	0.15	No trend
	Maximum	–	–	0.13	No trend

2.2.6 St. Croix River, Stillwater – Phosphorus

Flow-adjusted total phosphorus concentrations in the St. Croix River at Stillwater (Figure 22) have gradually declined since 1976, based on the Met Council analysis using QWTREND (Table 13 and Figure 23). Overall, total phosphorus concentrations have decreased by 13 and 27%, respectively, during the past 20 years (1999 to 2018) and 40 years (1979 to 2018).

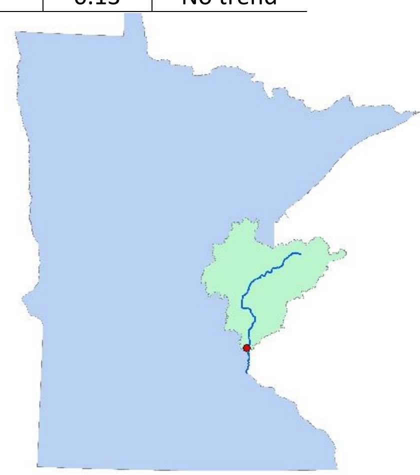

Figure 22. Watershed draining to St. Croix River at Stillwater monitoring site.

Table 13. Statistical Trend for Flow-Adjusted TP Concentration in the St. Croix River at Stillwater.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 2018	0.05 – 0.04	-28%	-0.00032	< 0.0001	⬇
Overall Trends					
20 years (1999 – 2018)	0.04 – 0.036	-13%	-0.00028	–	⬇
40 years (1979 – 2018)	0.05 – 0.04	-27%	-0.00033	–	⬇

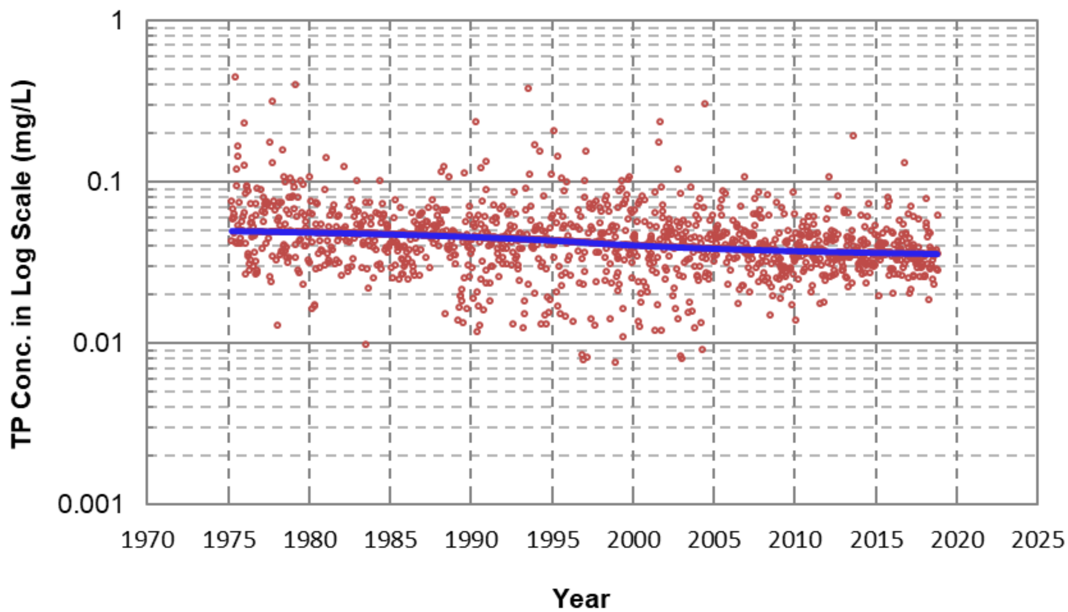

Figure 23. Statistical Trend for flow-adjusted TP Concentration in the St. Croix River at Stillwater.

Met Council did not find a statistically significant phosphorus load trend (non flow-adjusted) for the past 20 and 40 years at Stillwater (Table 14). Flows have increased in the past 20 years (Figure 24), but these increases are not statistically significant (p>0.1). The river flow changes may be offsetting at least some of the progress made in phosphorus concentration decreases.

Table 14. Statistical Trends for non flow-adjusted TP Loads in the St. Croix River at Stillwater. "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.77	No trend
40 years (1979 – 2018)	–	–	0.58	No trend

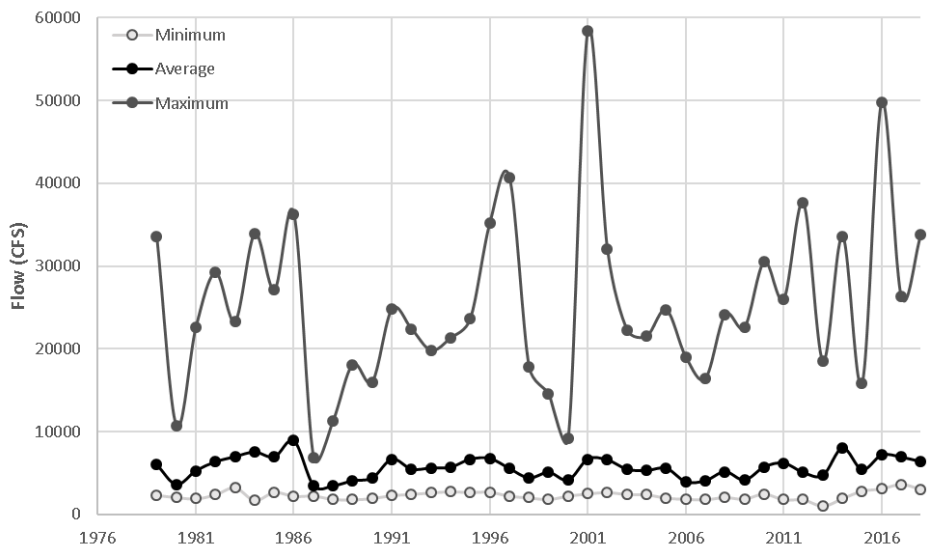

Figure 24. Annual minimum, maximum, and average daily flow in the St. Croix River at Stillwater (1979-2018).

2.3 Red River of the North

The USGS statistical trends focused on QWTREND analyses in the Red River and its tributaries for the period 2000 to 2015. While the modeling used available data also from 1995-1999 and 2016-2017 to help establish the 2000-2015 trend, the reported findings are only evaluated for statistical significance within the 2000-2015 period.

This report uses a Minnesota-specific subset of the sites in the full USGS report (Nustad and Vecchia, 2020) that also includes North Dakota and Manitoba. Additionally, this report uses different notation for indicating statistically significant trends than used by Nustad and Vecchia (2020). The USGS report uses lower p-value thresholds for denoting a significant trend, and also shows the direction of non-significant trends with high p-values. Refer to the complete USGS report for a more detailed breakdown of the trend findings in the Red River of the North Basin.

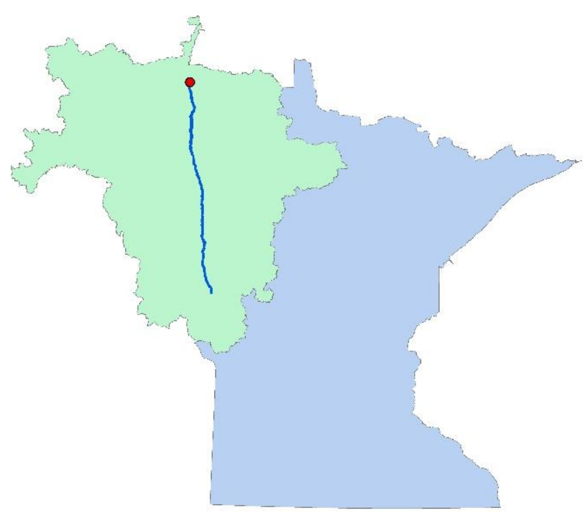

Figure 25. Approximate watershed draining to Red River at Emerson monitoring site.

The USGS results show Red River flow-adjusted phosphorus concentrations decreased by 24% since 2000 in the three upstream locations (Table 15). Further downstream in Grand Forks the river phosphorus concentration trends become non-significant ($p>0.1$). Further downstream yet, an increasing trend was found at the U.S. – Canada border in Emerson. The Emerson site is located just downstream from where the Pembina River flows in from Manitoba and North Dakota (Figure 25). The Pembina River shows increasing trends and is likely one reason for the increasing trend at Emerson. Other tributaries between Grand Forks and Emerson may also contribute to the increase as well;

however, a lack of data for those tributaries prevented inclusion in this analysis. It is possible that localized changes along the mainstem Red River may also contribute to the phosphorus increase at the Emerson site.

The Minnesota Red River tributaries evaluated by the USGS all show flow-adjusted phosphorus concentration decreases (13-51%), with the exception of Sand Hill River at Climax, which did not show a statistically significant trend (p>0.1). Flow-adjusted phosphorus load trends in the Red River Basin included in this report are identical to the concentration trends because of model assumptions and the approach used for trend calculation.

Table 15. Overview of Red River Basin phosphorus trends results at long-term Red River and Minnesota tributary monitoring sites. An increasing trend is denoted by "+" and a decreasing trend is "-." Non-significant trends (p<0.1) is denoted by "NS."

Red River and HUC-8 Tributaries	Parameter and Method (phosphorus)	Mid-range (2000-15)
Red River Emerson	Concentration and load (QWTREND flow-adjusted)	**+27%**
Red River Grand Forks	Concentration and load (R-QWTREND flow-adjusted)	**NS**
Red River Halstad	Concentration and load (R-QWTREND flow-adjusted)	**-24%**
Red River Harwood	Concentration and load (R-QWTREND flow-adjusted)	**-24%**
Red River Fargo	Concentration and load (R-QWTREND flow-adjusted)	**-24%**
Tributaries (MN)		
Wild Rice River Hendrum	Concentration (R-QWTREND flow-adjusted)	**-33%**
Sand Hill River Climax	Concentration (R-QWTREND flow-adjusted)	**NS**
Ottertail River Breckenridge	Concentration (R-QWTREND flow-adjusted)	**-56%**
Clearwater River Red Lake Falls	Concentration (R-QWTREND flow-adjusted)	**-21%**
Boix de Sioux River Doran	Concentration (R-QWTREND flow-adjusted)	**-13%**
Buffalo River Georgetown	Concentration (R-QWTREND flow-adjusted)	**-27%**

2.4 Lake Superior Basin

The St. Louis River contributes the most flow of any of Minnesota's rivers draining into Lake Superior (Figure 26). One site is included in the analysis: St. Louis River at Scanlon. The monitoring site is located just downstream from the town of Cloquet and several miles upstream from Duluth. The site is also upstream of where the river widens at Spirit Lake. Phosphorus concentrations are quite low in this river compared to the Mississippi and Red Rivers near the state borders.

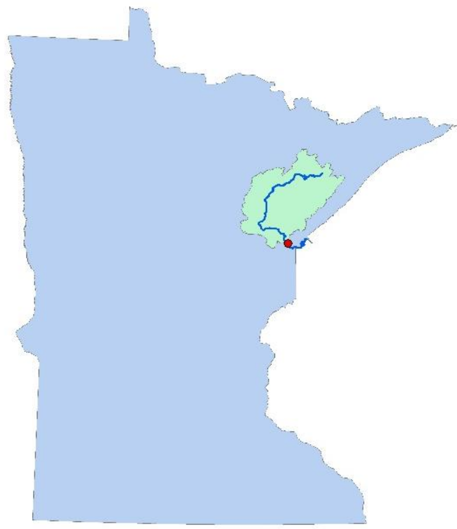

Figure 26. St. Louis River watershed.

Using the QWTREND model, the MPCA found flow-adjusted phosphorus concentrations decreased by 0.013 mg/l (30%) over a 43-year period from 1976 to 2018 (Table 16). Phosphorus concentrations decreased by 53% over the past 10 years (2009 to 2018). The mid-range concentration trend was not evaluated due to a data gap that affects that timeframe.

Table 16. Overview of St. Louis River at Scanlon Phosphorus concentration and load trend results.

Tributary	**Parameter and Method (phosphorus)**	**Recent (2009-18)**	**Mid-range (1998-17)**	**Long-Term (1976-2018)**
St. Louis River	Concentration (QWTREND flow-adjusted)	**-53%**		**-30%**
	Load flow-adjusted (EGRETci WRTDS)	**NS**	**NS**	**-44%**

The MPCA evaluated flow-adjusted phosphorus loads at the St. Louis River at Scanlon site using EGRETci WRTDS and found significant downward trends for the 43-year timeframe, with an estimated 44% decrease (73,360 pounds of phosphorus reduced). Flow-adjusted load decreases of about 40% during the 10- and 20-year timeframes were not significant (p=0.11, p=0.20), just over the significance threshold of p=0.1. The non flow-adjusted phosphorus loads show an increasing five-year rolling average since 2003 (Figure 27), coinciding with precipitation increases in this part of the state over that time period.

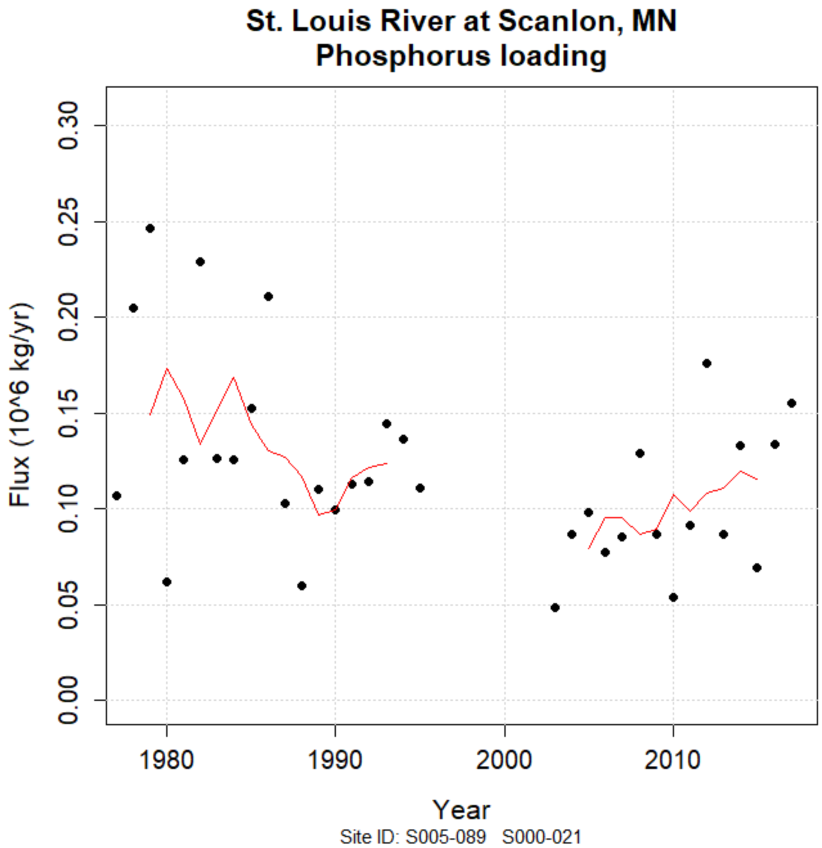

Figure 27. St. Louis River at Scanlon loads (not flow-adjusted) along with the five-year moving average.

3. Nitrate Results

The analysis for nitrate trends first uses a less rigorous statistical approach across the state, and then is followed by more in-depth analyses at certain key river monitoring sites in the (1) Mississippi River Basin, (2) Red River Basin, and (3) Lake Superior Basin.

3.1 Statewide Nitrate (MPCA)

Similar to phosphorus, the nitrate trend analyses include two levels: 1) data from MPCA monitoring sites assessed using the bootstrapped seasonal Kendall approach for 10, 20, and 40 year timeframes, and 2) 20-year mid-range trend analyses from Met Council, USGS and MPCA using QWTREND, R-QWTREND, and/or WRTDS EGRETci at long-term monitoring sites across Minnesota. Note that Met Council and USGS include additional river sites that are not included in the MPCA-assessed data sets.

3.1.1 MPCA Sites - Seasonal Kendall Test – 10, 20, and 40 Year Trends

The MPCA used the bootstrapped seasonal-Kendall statistical test for data collected at each of its monitoring sites during the past ten years or more to evaluate nitrate concentration trends. The vast majority of river nitrite+nitrate-N is nitrate (rather than the nitrite); therefore, this section refers to nitrite+nitrate as *nitrate*. The nitrate trend assessments included methods adjusting for year-to-year river flow variability, along with some analysis that did not adjust for flow. See the methods section at the beginning of this report for more information about the difference between flow-adjusted and non flow-adjusted techniques.

The analyses show that river nitrate concentrations have increased throughout much of Minnesota during recent decades. No sites had a decreasing nitrate concentration trend, although many sites have had no statistically significant trend. Other sites had nitrate levels below laboratory detection limits so often that trends analyses could not be performed. Using the flow-corrected seasonal-Kendall method, 14 of 38 sites (37%) with detectable nitrate showed increasing 10-year trends, with the other 63% showing non-significant trends. River monitoring results showed increasing 20-year nitrate trends at 5 out of 11 sites (45%). Statistically significant increasing trends were found at 75% (6 out of 8) of sites with 40-year records (Figure 28).

The non flow-adjusted trends showed 50% of sites with increasing trends, as compared to 37% of sites with increases using the flow-adjusted methods (Figure 28). At the same time that nitrate concentrations were increasing, river flows throughout most of southern and northeastern Minnesota were also increasing, causing even more sites to have statistically significant nitrate increases when not adjusting for flow.

The majority of the 10-year nitrate increases were found in the central and southwestern part of the state (Figure 29). The 20-year increases were more scattered at the five sites with increases (Figure 30).

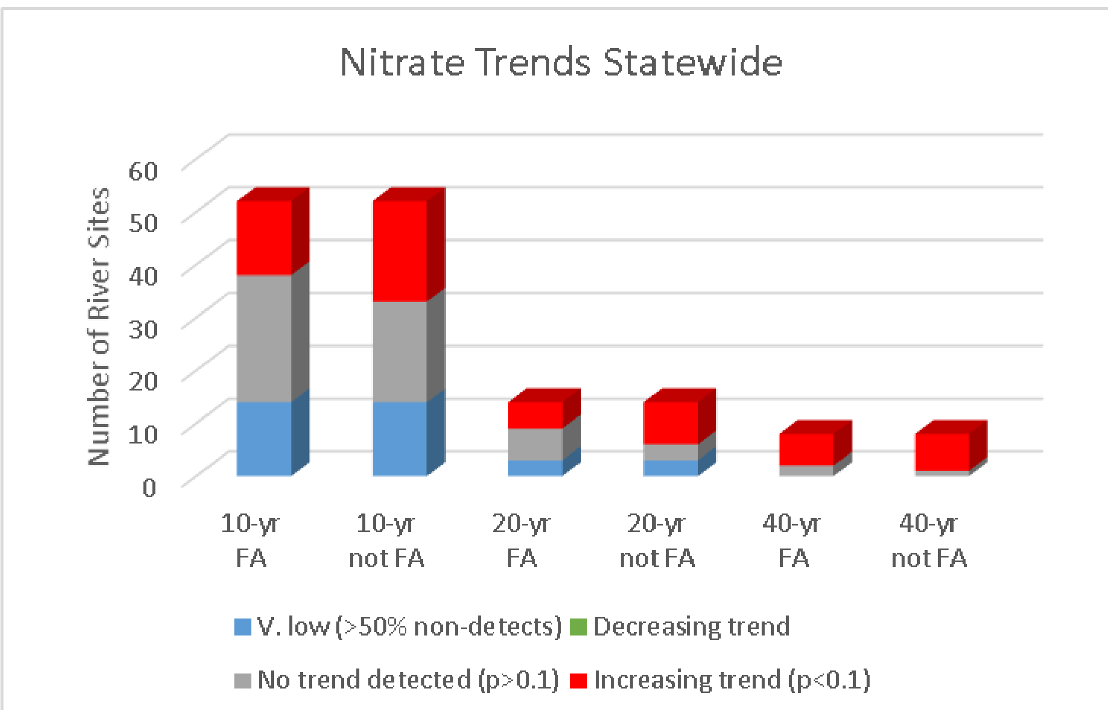

Figure 28. Bootstrapped Seasonal Kendall nitrate concentration trend results using both flow-adjusted (FA) and non flow-adjusted (not FA) techniques at MPCA monitored river sites across Minnesota.

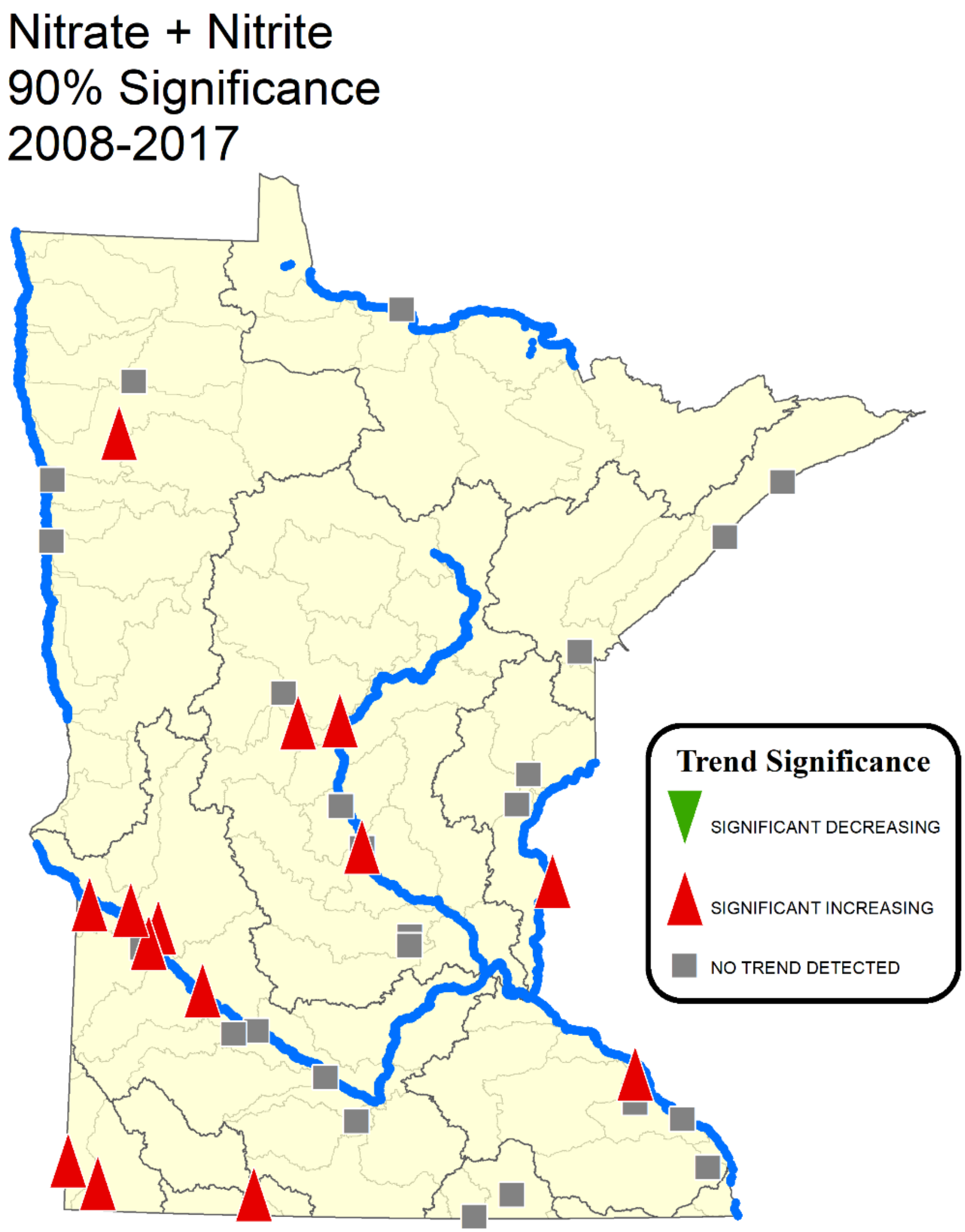

Figure 29. Recent (2008-2017) nitrate trends at MPCA sites assessed using a flow-adjusted Seasonal Kendall approach.

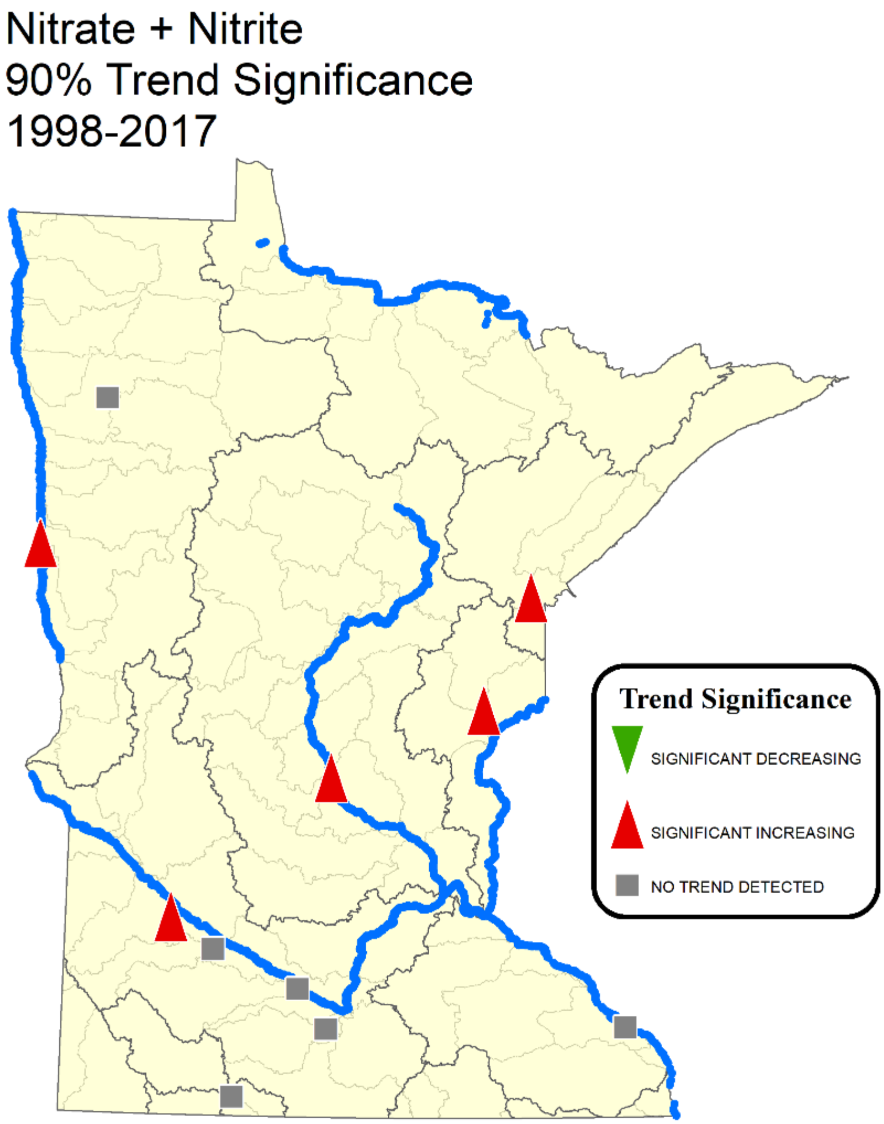

Figure 30. Mid-range (1998-2017) nitrate+nitrite trends at MPCA sites assessed using a flow-adjusted Seasonal Kendall approach.

3.1.2 Statewide Mid-range Nitrate Trends from Met Council, USGS, and MPCA

Rigorous statistical analyses using QWTREND and R-QWTREND (concentration trends) and/or EGRETci WRTDS (load trends) were also performed for nitrate statewide.

Mid-range (approximately 20-year) flow-adjusted nitrate concentration trends were conducted using QWTREND and/or EGRETci WRTDS at the same key major river sites as previously described for phosphorus and shown in Figure 31. QWTREND was used to assess trends at all mapped sites in Figure 31, except that the flow-adjusted Seasonal Kendall test used at tributaries to the Minnesota River, along with the Sauk River and Kettle River.

Half of the mid-range sites show increasing trends (14 of 28) and only 3 of 28 (11%) sites showed a decreasing trend. Eleven of the 28 sites had no significant trend detected. More details about nitrate trend results are described below for each site where the QWTREND or R-QWTREND method was used by either the USGS, Met Council or MPCA.

In general, nitrate concentration trend directions for mid-range trends in figure 30 are similar to the mid-range trends in Figure 31, which includes several different sites and different statistical methods.

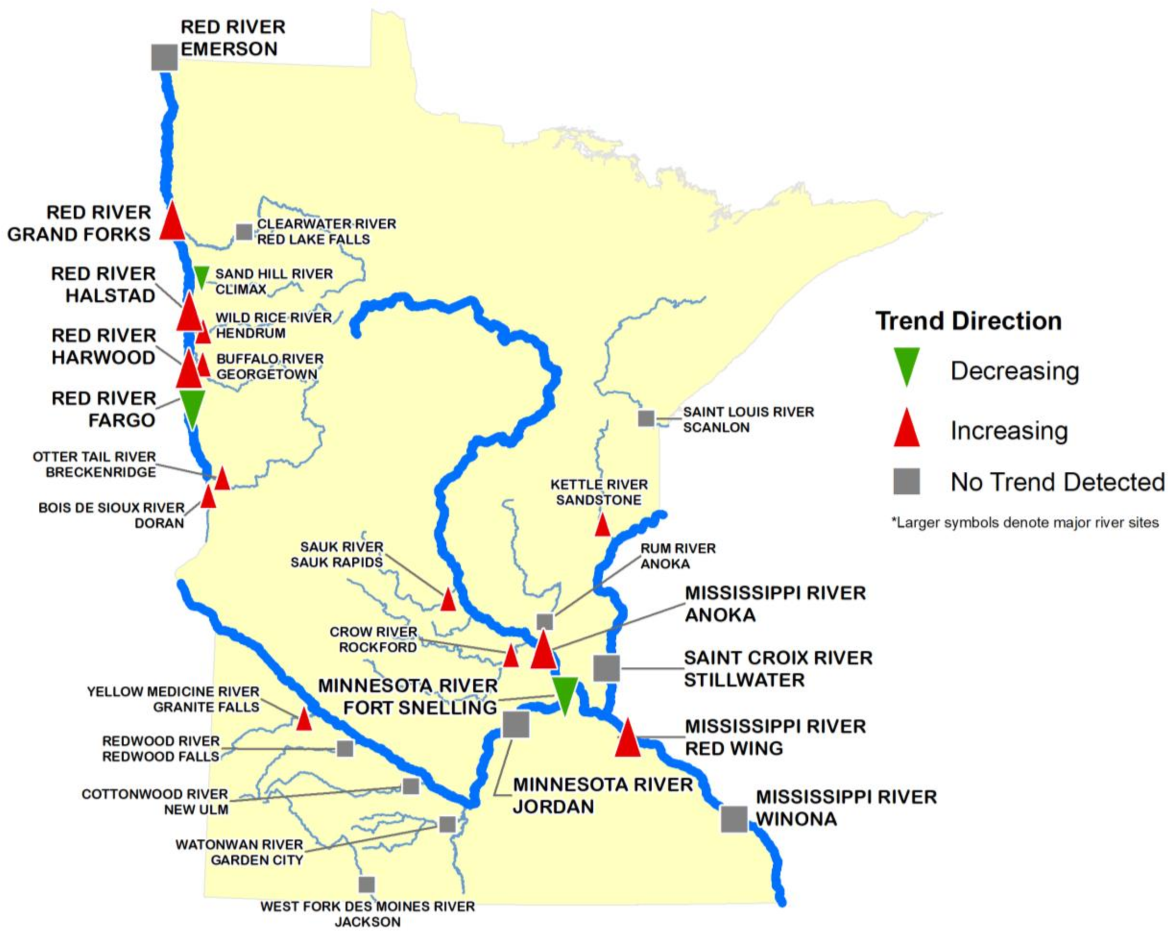

Figure 31. River monitoring site locations at sites with enough information to determine mid-range (approximately 20-year) flow-adjusted nitrate concentration trends. Large symbols represent major river sites and small symbols represent tributary river sites.

3.2 Mississippi River Basin

An overview of nitrate trends in the Mississippi River and its major tributaries is shown in Table 17. Trends over the long-term (37-43 years) show increasing flow-adjusted concentration trends in the Mississippi River (68% to 162%) and Minnesota River at Fort Snelling (21%). Long-term nitrate concentration increases were non-significant in the St. Croix River Stillwater and Minnesota River

Jordan. The mid-range (approximately 20-year) flow-adjusted nitrate concentration trends were more varied, with two increases of 25 and 34%, one decrease by 15%, and three non-significant increases.

Nitrate flow-adjusted load increases were not significant at the Mississippi River Winona site, but were significant for the 40-year trends at the Mississippi River Red Wing site (53-54% increases in both flow-adjusted and non flow-adjusted loads). Further upstream at the Minnesota River sites and the Mississippi River Anoka site, the non flow-adjusted load increases were fairly close to being significant, with p-values between 0.11 and 0.22 in.

Table 17. Overview of Mississippi River Basin nitrate trends results for concentration and load at long-term major river monitoring sites.

An increasing trend is denoted by "+" and a decreasing trend is "-." Non-significant trends at a p<0.1 is denoted by "NS."

Mississippi River and Major Tributaries	Parameter and Method	Recent (~ 10 yr)	Mid-range (~ 20 yr)	Long-Term (~ 40 yr)
Mississippi River Winona	Concentration (QWTREND flow-adjusted)	**NS**	**NS**	**+68%**
	Load flow-adjusted (EGRETci-WRTDS flow- adjusted)	**NS**	**NS**	**NS**
Mississippi River Red Wing	Concentration (QWTREND flow-adjusted)		**+25%**	**+154%**
	Load flow-adjusted (EGRETci-WRTDS)	**NS**	**NS**	**+54%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**+62%**	**+53%**
Mississippi River Anoka	Concentration (QWTREND flow-adjusted)		**+34%**	**+162%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.14	**NS** P=0.16
Minnesota River Jordan	Concentration (QWTREND flow-adjusted)		**NS**	**NS**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.16	**NS** P=0.13
Minnesota River Fort Snelling	Concentration (QWTREND flow-adjusted)		**-15%**	**+21%**
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.11	**NS** P=0.22
St. Croix River Stillwater	Concentration (QWTREND flow-adjusted)		**NS** P=0.	**NS** P=0.
	Load (Mann Kendall of annual loads, not flow-adjusted)		**NS** P=0.63	**NS** P=0.97
Crow River Rockford	Concentration (QWTREND flow-adjusted)		**+55%**	

The Crow River, a major tributary delivering nutrients to the Upper Mississippi River, showed a 55% nitrate concentration increase from 1999-2018. Trends on many other different HUC-8 tributaries in the Mississippi Basin were calculated by the MPCA using the seasonal Kendall method, as previously discussed.

3.2.1 Mississippi River at Winona - Nitrate

For the Mississippi River Winona site near the state border with Iowa (Figure 32), this analysis assessed flow-adjusted nitrate concentration trends over three time periods representing the past 11, 21 and 36 years. The long-term (36-year) trends show a 68% increase using the QWTREND model. However, the recent (11-year) and mid-range (21-year) increases were not statistically significant.

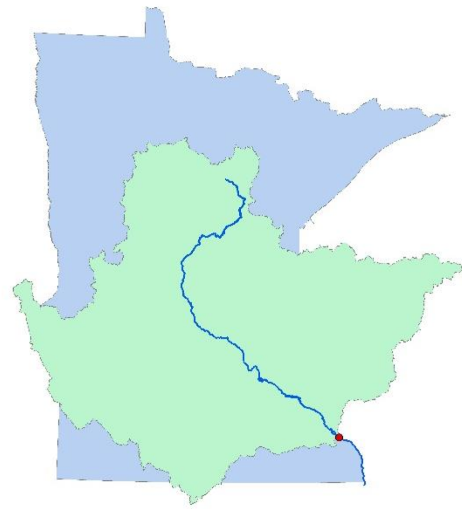

Figure 32. Watershed draining to Mississippi River at Winona monitoring site.

Using EGRETci WRTDS, we also evaluated the flow-adjusted nitrate load trends for the short-term (2008-2018), mid-range (2001-2018) and long-term (1982-2018) timeframes. The load results show non-significant flow-adjusted nitrate load increases for these periods.

The non flow-adjusted nitrate loads viewed as a five-year rolling average (Figure 33) show inconsistent trends over the decades, but shows an increasing trend since 2007.

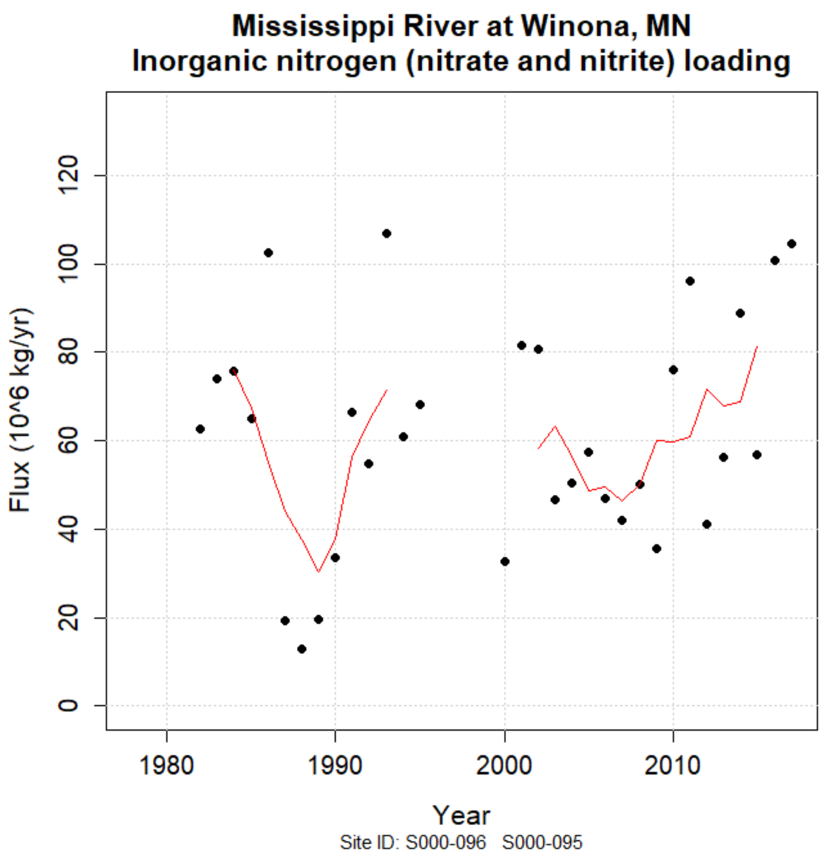

Figure 33. Mississippi River at Winona five-year rolling average nitrate loads (non flow-adjusted). Loads were calculated with the EGRETci WRTDS model.

3.2.2 Mississippi River at Red Wing (Lock and Dam #3) – Nitrate

The Met Council analysis using the QWTREND program shows that nitrate flow-adjusted concentrations increased in the Mississippi River at Red Wing (Figure 34) by 25 and 154% over the past 20 and 40 years, respectively. Nitrate concentration changes at this site are best represented by a two-trend model ($p < 0.0001$) over the assessment period of 1976 to 2018 (Table 18 and Figure 35). Nitrate concentrations increased markedly from 1976 to 1982, followed by a more gradual increase between 1983 and 2018.

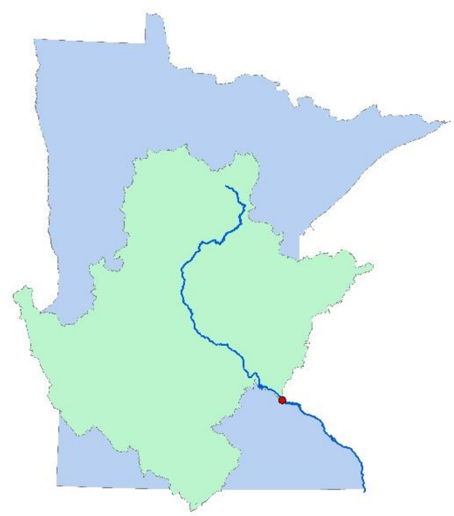

Figure 34. Watershed draining to Mississippi River at Red Wing monitoring site.

Table 18. Statistical Trends for NOx Concentration in the Mississippi River at Lock and Dam 3.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 1982	0.58 – 1.39	142%	0.12	< 0.0001	↑
1983 – 2018	1.39 – 2.03	46%	0.018	< 0.0001	↑
Overall Trends					
20 years (1999 – 2018)	1.62 – 2.03	25%	0.020	–	↑
40 years (1979 – 2018)	0.80 – 2.02	154%	0.031	–	↑

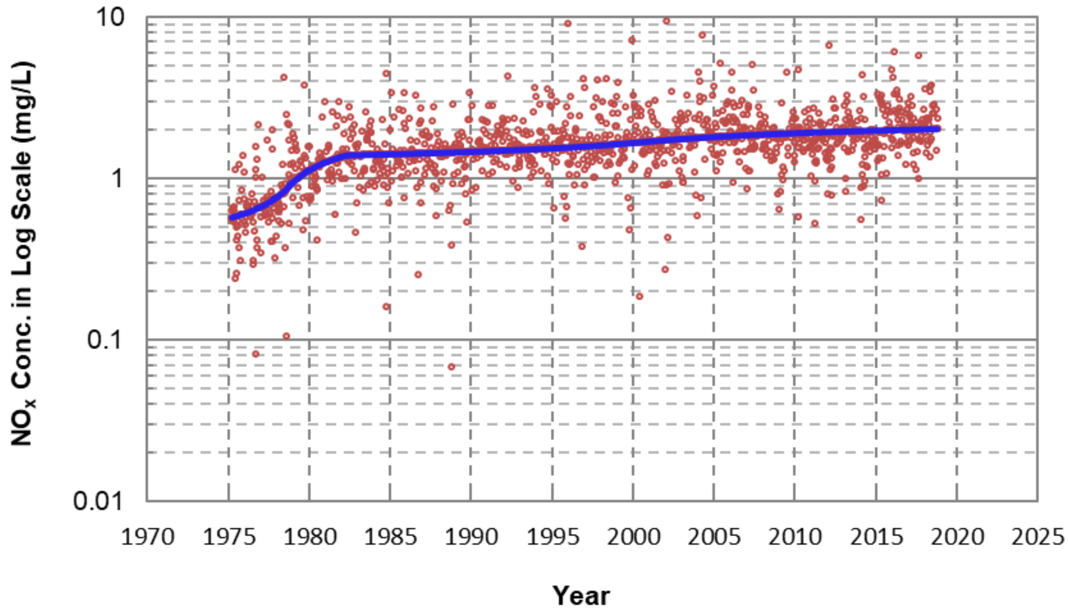

Figure 35. Statistical Trends for NOx Concentration in the Mississippi River at Lock and Dam 3.

A separate analysis of non flow-adjusted load trends showed 62% and 53% nitrate load increases during the past 20 and 40 years, respectively (Table 19 and Figure 36). This is not surprising since loads reflect the combination of concentrations and river flow, and both have increased. Flows have especially increased during the past 20 years. Total nitrogen loads show a similar pattern over time as nitrate.

Table 19. Statistical Trends for NOx Loads in the Mississippi River at Lock and Dam 3.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	1,850,000	62%	0.09	↑
40 years (1979 – 2018)	723,000	53%	0.09	↑

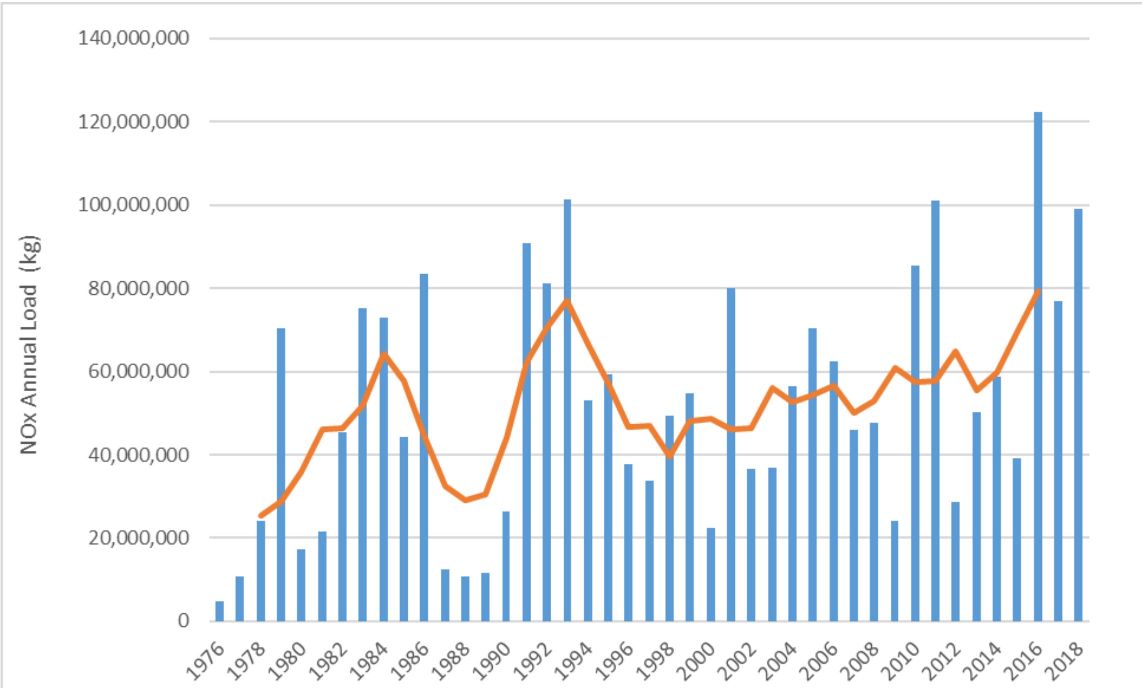

Figure 36. Annual NOx Loads in the Mississippi River Red Wing along with the five-year rolling average (orange line).

The MPCA evaluated flow-adjusted nitrate load trends for the recent, mid-range and long-term periods of 2007-2018, 1997-2018, and 1977-2018. The EGRETci WRTDS trend results show nitrate annual flow-adjusted load increases of 10.2, 16.6 and 21.7 million pounds per year for the 12-, 22- and 42-year periods. However, the load trends were only significant ($p<0.1$) for the long-term period.

3.2.3 Mississippi River at Anoka – Nitrate

Met Council found flow-adjusted nitrate concentration increases of 34% and 162% over the past 20 and 40 years, respectively, in the Mississippi River at Anoka (Figure 37). Similar to the Mississippi River at Red Wing, the increases were greatest during the 1976 to 1983 timeframe and more gradual from 1984 to 2018 (Table 20 and Figure 38).

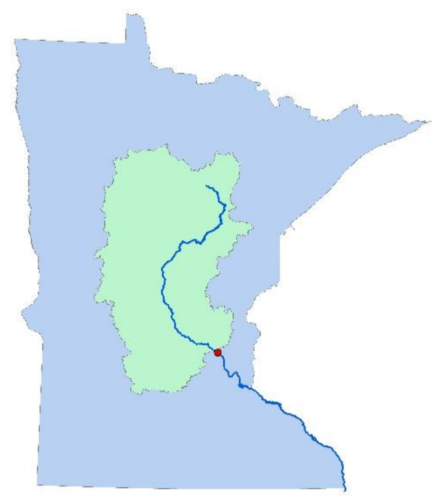

Figure 37. Watershed draining to Mississippi River at Anoka monitoring site.

Table 20. Statistical Trends for NOx Concentration in the Mississippi River at Anoka.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 1983	0.28 – 0.57	103%	0.036	< 0.0001	↑
1984 – 2018	0.57 – 0.90	59%	0.0095	< 0.0001	↑
Overall Trends					
20 years (1999 – 2018)	0.67 – 0.90	34%	0.011	–	↑
40 years (1979 – 2018)	0.34 – 0.90	162%	0.014	–	↑

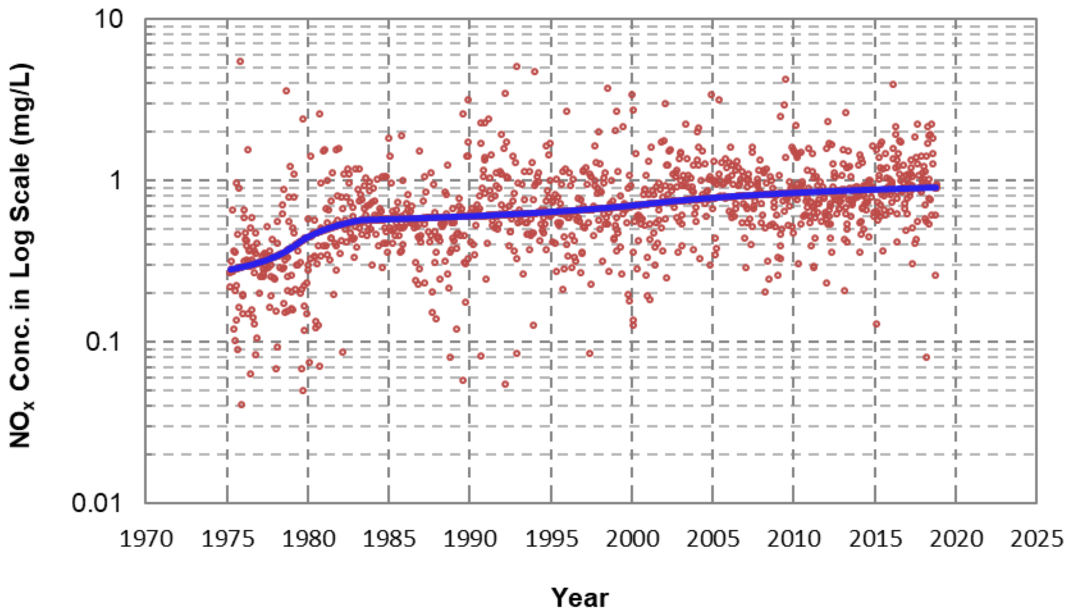

Figure 38. Statistical Trends for flow-adjusted nitrate (NOx) Concentration in the Mississippi River at Anoka

A separate analysis of non flow-adjusted load trends showed an increase at Anoka, but was not statistically significant for either the 20- or 40-year periods (p= 0.14 and 0.16; Table 21). The river flow trends at this site were not statistically significant. The year-to-year flow variability reduce the likelihood of showing statistically significant load trends.

Table 21. Statistical Trends for Non Flow-Adjusted Nitrate Loads in the Mississippi River at Anoka. "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.14	No trend
40 years (1979 – 2018)	–	–	0.16	No trend

3.2.4 Minnesota River, Jordan – Nitrate

Flow-adjusted nitrate concentrations in the Minnesota River at Jordan (Figure 39) had three significant trend periods (p = 0.01) between 1979 and 2018 (Table 22 and Figure 40). The trend identified for the 1979 to 2004 period was not statistically significant. However, the high nitrate concentrations at Jordan started to decrease by 32% from 2005 to 2011, followed by an increase of 40% from 2012 to 2018.

Even though significant trends were found in the periods noted above, when assessing the pre-defined 20-year and 40-year periods, no overall changes were provided for the past 20 and 40 years because one of the sub-trends during these time frames (1979-2004) is not statistically significant.

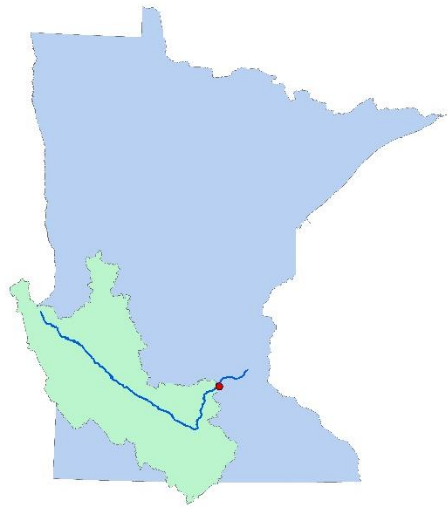

Figure 39. Watershed draining to Minnesota River at Jordan monitoring site.

Table 22. Statistical Trends for Nitrate Concentration in the Minnesota River at Jordan.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1979 – 2004	–	–	–	0.19	No trend
2005 – 2011	2.92 – 1.98	-32%	-0.14	0.0004	
2012 – 2018	1.98 – 2.77	40%	0.11	0.05	
Overall Trends					
20 years (1999 – 2018)	–	–	–	–	NA
40 years (1979 – 2018)	–	–	–	–	NA

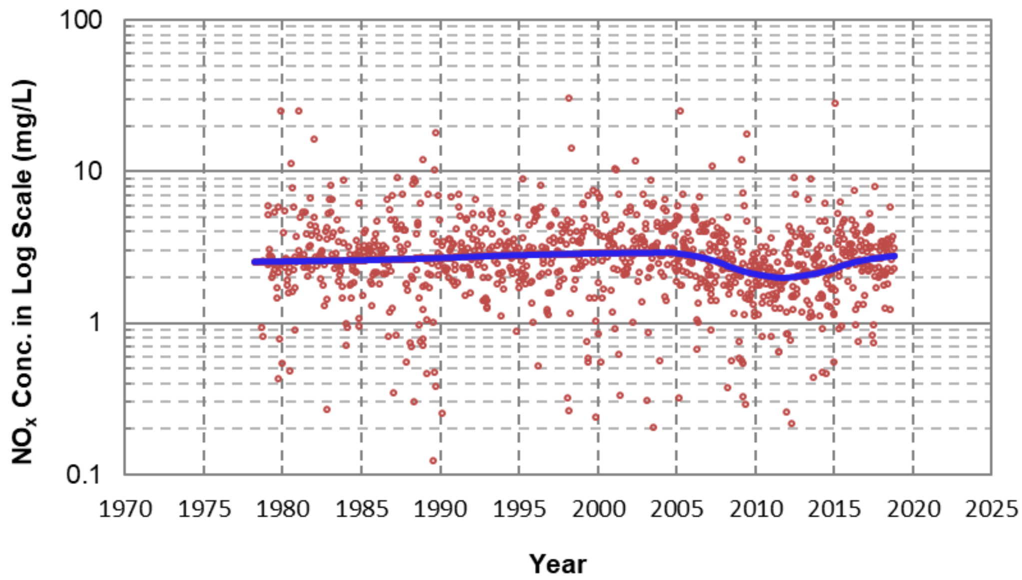

Figure 40. Statistical Trends for Flow-Adjusted Nitrate (NOx) Concentration in the Minnesota River at Jordan.

The highest nitrate load on record through 2018 at Jordan occurred in 2016. Nitrate load increases were relatively close to being significant, but did not meet the 90% confidence criteria for the past 20 and 40 years in the Minnesota River at Jordan (Table 23). Even though flows increased by 68% during the past 20 years, the annual variability in loads was quite high and thus the load trends were not significant.

The non flow-adjusted nitrate loads viewed as a five-year rolling average (Figure 41) shows what appears to be a nitrate load increase between 1998 and 2016.

Table 23. Statistical Trends for Non Flow-adjusted Nitrate (NOx) Loads in the Minnesota River at Jordan. "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.16	No trend
40 years (1979 – 2018)	–	–	0.13	No trend

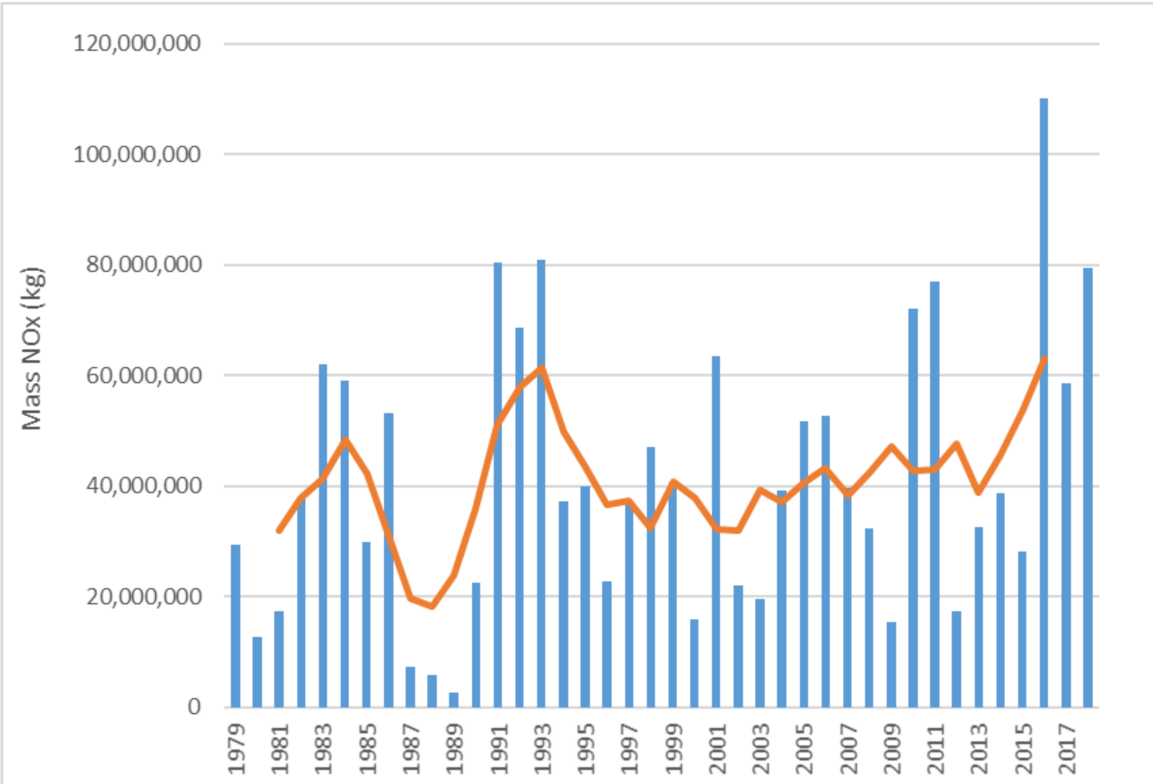

Figure 41. Annual Non Flow-Adjusted Nitrate (NOx) Loads in the Minnesota River at Jordan (1979-2018).

3.2.5 Minnesota River, Fort Snelling – Nitrate

Based on the Met Council QWTREND analysis, nitrate concentration changes in the Minnesota River at Fort Snelling are best represented by an increase from 1976 to 2004 followed by a decrease from 2005 to 2018 (Table 24 and Figure 43).

Overall, nitrate concentrations decreased by 15% from 2005 to 2018 but increased by 21% from 1979 to 2018. While the specific periods of change are different between the Minnesota River Jordan site and the nearby Minnesota River Fort Snelling site, data from both sites indicate that there has not been a clear and consistent concentration trend direction over the past 20 and 40 years at these downstream reaches of the Minnesota River.

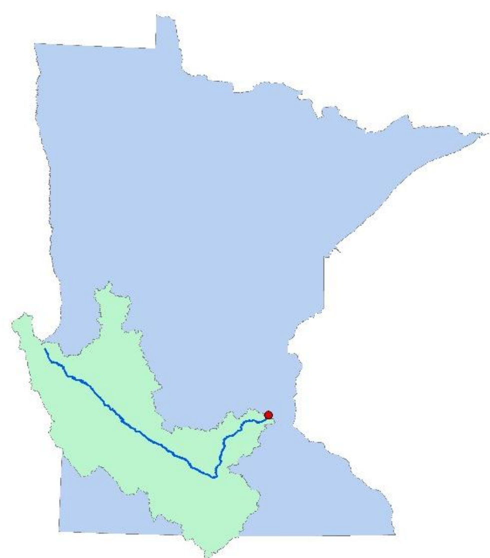

Figure 42. Minnesota River at Fort Snelling drainage area.

Table 24. Statistical Trends for Nitrate Concentration in the Minnesota River at Fort Snelling.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 2004	2.15– 3.32	54%	0.040	< 0.0001	⬆
2005 – 2018	3.32 – 2.66	-20%	-0.047	0.05	⬇
Overall Trends					
20 years (1999 – 2018)	3.1 – 2.7	-15%	-0.024	–	⬇
40 years (1979 – 2018)	2.2 – 2.7	21%	0.011	–	⬆

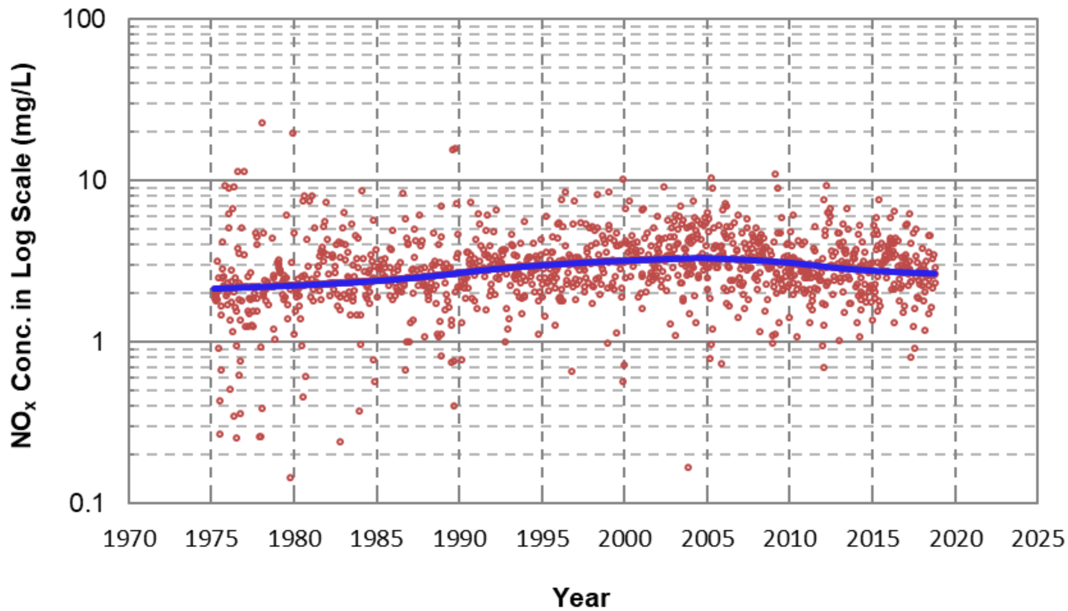

Figure 43. Statistical Trends for Flow-Adjusted Nitrate (NOx) Concentration in the Minnesota River at Fort Snelling.

Met Council did not find a statistically significant non flow-adjusted nitrate load increase for the past 20 and 40 years at Fort Snelling. Similar to the Minnesota River Jordan site, the p-values slightly exceeded the 90% confidence threshold, especially for the 20-year period (Table 25).

Table 25. Statistical Trends for Non Flow-Adjusted Nitrate Loads in the Minnesota River at Fort Snelling. "No trend" means no trend detected with the trend analysis methods.

Trend Period	Change Rate (kg/yr)	Change Rate (%)	*p*	Trend
20 years (1999 – 2018)	–	–	0.11	No trend
40 years (1979 – 2018)	–	–	0.22	No trend

3.2.6 St. Croix River, Stillwater – Nitrate

Nitrate flow-adjusted concentrations in the St. Croix River at Stillwater (Figure 44) gradually increased between 1976 and 2003, with a total change in concentration of 49%. No statistically significant trends were reported for the 20-and 40-year periods because one of the subtrends was not statistically significant (Table 26 and Figure 45).

The St. Croix River at Stillwater is one location where total nitrogen concentration trends differed from nitrate. Total nitrogen decreased slightly over 20 years (-3%) and 40 years (-6%). Both nitrate and total nitrogen are relatively low at this site, and the organic forms of nitrogen constitute a higher fraction of the total nitrogen as compared to most other rivers evaluated, helping explain why nitrate and total nitrogen trends differ.

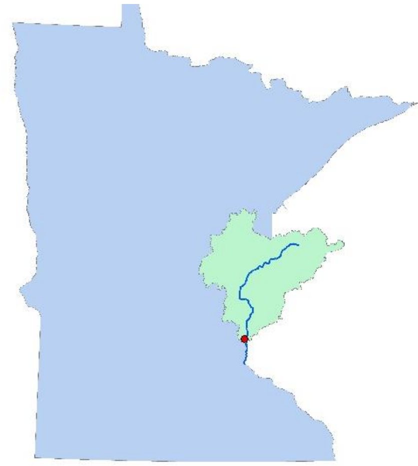

Figure 44. Watershed draining to St. Croix River at Stillwater monitoring site.

Table 26. Statistical Trends for Flow-Adjusted Nitrate (NOx) Concentration in the St. Croix River at Stillwater.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1976 – 2003	0.22 – 0.32	49%	0.0038	< 0.0001	↑
2004 – 2018	–	–	–	0.24	No trend
Overall Trends					
20 years (1999 – 2018)	–	–	–	–	–
40 years (1979 – 2018)	–	–	–	–	–

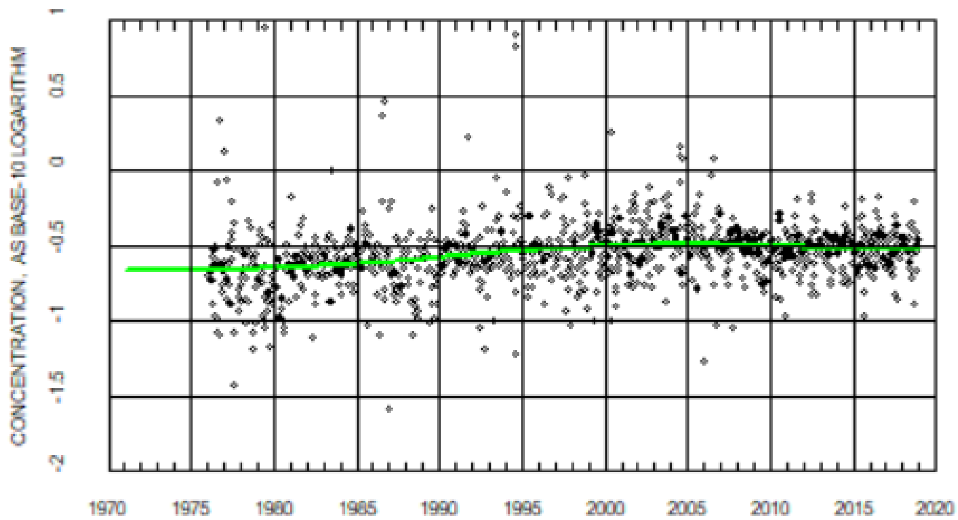

Figure 45. Statistical Trends for NOx Concentration in the St. Croix River at Stillwater.

No statistically significant trends were observed for 20- and 40-year non flow-adjusted nitrate loads in the St. Croix Stillwater (Table 27). This is not surprising, given the lack of either a flow trend or a concentration trend in the St. Croix Stillwater site during the past 20 and 40 years.

Table 27. Statistical Trends for Non Flow-Adjusted Nitrate (NOx) Loads in the St. Croix River at Stillwater.

Trend Period	**Change Rate (kg/yr)**	**Change Rate (%)**	***p***	**Trend**
20 years (1999 – 2018)	–	–	0.63	No trend
40 years (1979 – 2018)	–	–	0.97	No trend

3.2.7 Crow River, Rockford – Nitrate

Based on the Met Council QWTREND analysis, flow-adjusted nitrate concentration changes in the Crow River at Rockford can be best represented by a three-period trend model (p = 0.0003) over the assessment period from 1999 to 2018. Nitrate concentrations increased between 1999 and 2005, decreased from 2006 to 2012, then increased again from 2013 to 2018 (Table 28).

Overall, nitrate concentrations increased by 55% from 1999 to 2018, indicating a decline in water quality as it relates to NO_x during the recent 20 years.

Table 28. Statistical Trends for Nitrate Concentration in Crow River at Rockford.

Trend Period	Concentration (mg/L)	Change in Concentration (%)	Change Rate (mg/L/yr)	*p*	Trend
1999 – 2005	1.02 – 1.81	78%	0.11	0.002	↑
2006 – 2012	1.81 – 1.00	-45%	-0.12	< 0.0001	↓
2013 – 2018	1.00 – 1.58	58%	0.096	0.014	↑
Overall Trends					
20 years (1999 – 2018)	1.02 – 1.58	55%	0.028	–	↑

3.3 Red River of the North

Red River of the North flow-adjusted nitrate concentrations increased by 21-50% since 2000 at the Harwood, Halstad, and Grand Forks sites. However, concentrations decreased at the Fargo site, upstream from these other locations, and were not significant at the most downstream location at Emerson (Table 29 and Figure 31). The Emerson site is located just downstream from where the Pembina River flows in from Manitoba and North Dakota (Figure 46). The Pembina River has had decreasing nitrate trends and may be one reason that the Red River trend changes from an increase at Grand Forks to a non-significant trend further downstream near the Canadian border at Emerson.

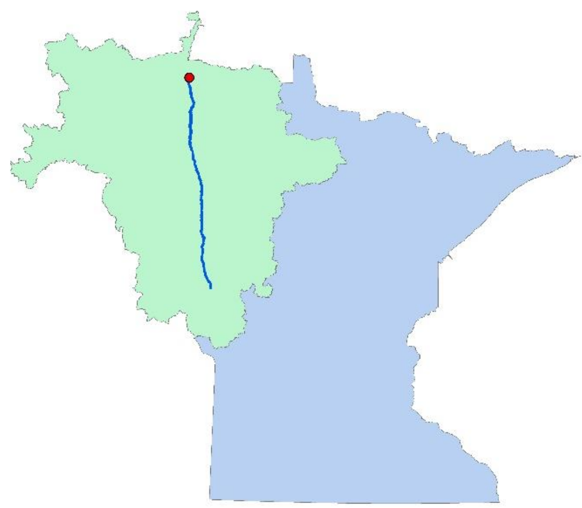

Figure 46. Watershed draining to Red River at Emerson monitoring site.

The Minnesota tributaries of the Red River evaluated by the USGS show four rivers with increasing nitrate concentration trends (48-181%), one river with a decrease (39%), and one non-significant trend (p>0.1). The predominantly increasing trends in these tributaries is generally consistent with the predominantly increasing trends in the Red River.

The USGS also assessed flow-adjusted total nitrogen concentration trends. The total nitrogen trends generally parallel the direction of nitrate trends. One difference was found at Emerson where total nitrogen increased by 8% (p=0.06), compared to non-significant nitrate trends.

More information about the nutrient trends in the Red River Basin can be found in Nustad and Vecchia (2020) found at www.[USGS report link – Pending Final web site placement]

Table 29. Overview of Red River Basin nitrate trend results at long-term Red River and Minnesota tributary monitoring sites. An increasing trend is denoted by "+" and a decreasing trend is "-." Non-significant trends at a p<0.1 is denoted by "NS."

Red River and HUC-8 Tributaries	Parameter and Method	Mid-range (2000-15)
Red River Emerson	Concentration and load (R-QWTREND flow-adjusted)	**NS**
Red River Grand Forks	Concentration and load (R-QWTREND flow-adjusted)	**+21%**
Red River Halstad	Concentration and load (R-QWTREND flow-adjusted)	**+28%**
Red River Harwood	Concentration and load (R-QWTREND flow-adjusted)	**+50%**
Red River Fargo	Concentration and load (R-QWTREND flow-adjusted)	**-39%**
Tributaries (MN)		
Wild Rice River Hendrum	Concentration and load (R-QWTREND flow-adjusted)	**+181%**
Sand Hill River Climax	Concentration and load (R-QWTREND flow-adjusted)	**-39%**
Ottertail River Breckenridge	Concentration and load (R-QWTREND flow-adjusted)	**+159%**
Clearwater River Red Lake Falls	Concentration and load (R-QWTREND flow-adjusted)	**NS**
Boix de Sioux River Doran	Concentration and load (R-QWTREND flow-adjusted)	**+134%**
Buffalo River Georgetown	Concentration and load (R-QWTREND flow-adjusted)	**+48%**

3.4 Lake Superior Basin

The St. Louis River at Scanlon site represents trends in the Lake Superior Basin for this analysis (Figure 47). Using the QWTREND model, the MPCA found flow-adjusted nitrate concentrations increased by 54% over the 43-year record from 1976 to 2018 (Table 30). This 54% increase during the long-term record represents a very small magnitude of change (0.042 mg/l). Analysis of the past 10 years (2009-2018) shows nitrate concentrations decreased by 11%.

The flow-adjusted nitrate load trends evaluated using EGRETci WRTDS show non-significant (p>0.1) trends for recent, medium-range and long-term periods (2008-2018, 1998-2018, and 1977-2018). The non flow-adjusted load five-year moving average shows an increasing trend since about 2004, which is likely driven by increasing precipitation and flows in the northeastern part of the state (Figure 48).

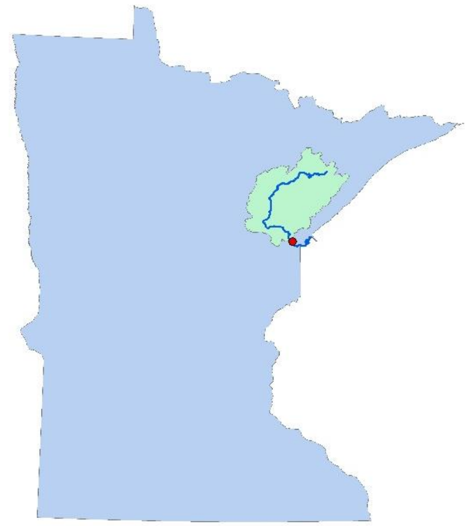

Figure 47. St. Louis River drainage area.

Table 30. Overview of St. Louis River nitrate trend results at long-term monitoring sites.
An increasing trend is denoted by "+" and a decreasing trend is "-." Non-significant trends at a p<0.1 is denoted by "NS."

Tributary	Parameter and Method (nitrate)	Recent (2009-18)	Mid-range (1997-2018)	Long-Term (1976-2018)
St. Louis River	Concentration (QWTREND flow-adjusted)	**-11%**	**NS**	**+54%**
	Load flow-adjusted (EGRETci WRTDS)	**NS**	**NS**	**NS**

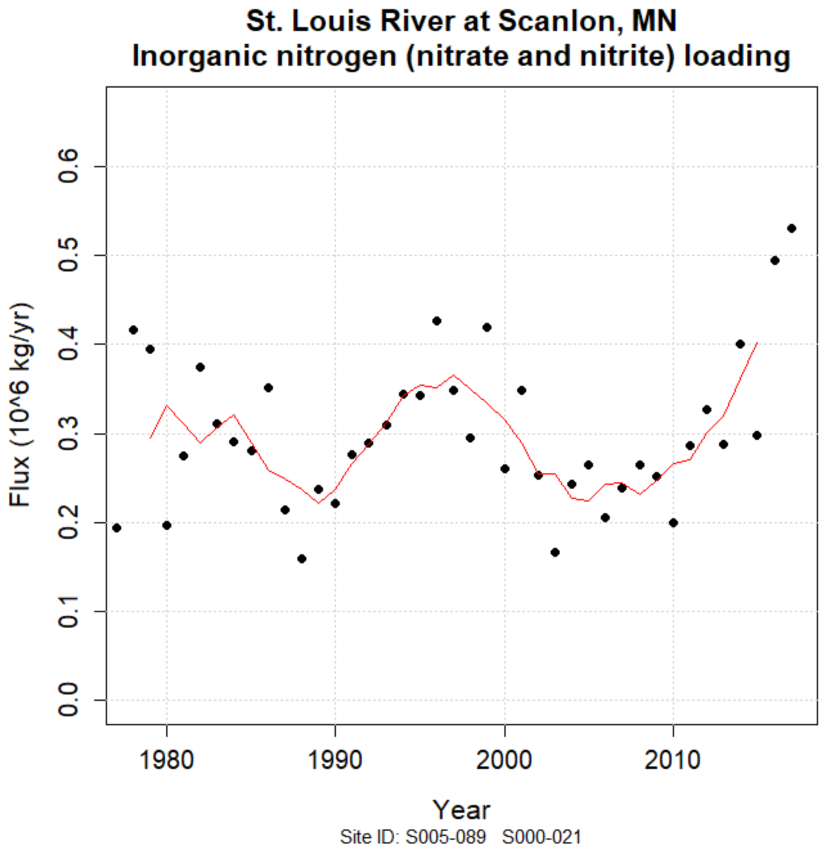

Figure 48. Non flow-adjusted nitrate load at the St. Louis River Scanlon site from 1978 through 2018, with the five-year moving average (red line).

4. Findings Overview

Because relatively long periods of time are needed to evaluate trends, definitive statements about the magnitude of river nutrient changes during 2014 to 2018 (since finalizing the 2014 NRS) are limited. Ten and 20-year trends, however, were determined, reflecting changes occurring since the NRS baselines in the late 1990's and the passing of the Clean Water Land and Legacy Amendment in 2008.

Based on intensive river monitoring efforts across the state, phosphorus concentrations have generally decreased and nitrate-nitrogen and total nitrogen concentrations have generally increased over the past 10 and 20 years. However, regional differences exist and high year-to-year variability makes it difficult to confidently show trend directions at many of the monitoring locations.

The findings indicate that our efforts to reduce river phosphorus concentrations have been working; whereas our efforts to reduce nitrate have not been as effective thus far.

Both flow-adjusted and non-flow adjusted evaluation methods were used to create a more complete picture of how nutrients are changing in Minnesota rivers. Flow-adjusted methods are intended to separate the water quality effects caused by human changes on the land and cities from those caused by variability in precipitation and river flow.

When river flow variability is not accounted for (non flow-adjusted) phosphorus concentration decreases are being at least partially offset by increased flow, such that phosphorus load reductions are not statistically significant at the primary Mississippi River monitoring sites. Nitrate loads show increasing trends at some sites, since both concentration and flow are increasing.

Flow-adjusted concentration trends

When using the flow-adjusted techniques for the past decade (2008 to 2017), 24 of 50 (48%) river sites showed *decreasing* phosphorus trends, with all other sites showing no significant trend ($p>0.1$). This indicates that efforts to reduce phosphorus in recent years have been making a difference. For nitrate-nitrogen, the dominant form of nitrogen in polluted rivers, 14 of 38 sites (37%) had *increases* with the rest having no trend. This suggests that efforts to reduce nitrate thus far are either insufficient and/or not enough time has elapsed for the full effects of our efforts to be seen in rivers.

Similar patterns were found when looking at flow-adjusted concentration trends over the past two decades. The Mississippi River monitoring sites near the Twin Cities had phosphorus concentration *decreases* of 21 to 26%, whereas nitrate had 20-year *increases* in the range of 25 to 34%. Further downstream near the Iowa border, the Mississippi River phosphorus concentrations have dropped by 50%, and nitrate was too variable to provide a high confidence in trends.

The Minnesota River, a high nutrient-loading tributary to the Mississippi River, has had flow-adjusted phosphorus concentration decreases of about 17% during the past 20 years. However, at Jordan Minnesota, this decrease has been shifting to increasing concentrations since 2009. The Minnesota River has had mixed 20-year nitrate trends, but has been showing an increase since 2012. Downstream from Jordan, the Minnesota River at Fort Snelling has had decreasing nitrate concentrations since 2005. Additional years of monitoring at the Minnesota River is needed to better understand recent flow-adjusted nitrate concentration trends.

In the Red River of the North, flow-adjusted phosphorus concentrations over the past two decades have decreased in the upstream reaches but increased at the state border, just downstream of the Pembina River. With a few exceptions, nitrate concentrations increased across the Red River Basin. At the state border with Canada, the Red River flow-adjusted nitrate concentration trend was not considered statistically significant.

In the St. Louis River, flow-adjusted phosphorus concentrations decreased significantly during the past 10 and 43-year time periods. A data gap in the middle of the record prevented analysis of 20-year trends. Nitrate concentrations have increased since the mid-1970's, but have decreased within the past decade.

Load trends

Whereas reducing nutrient *concentrations* is important for local water quality and drinking water, reducing nutrient *loads* is important for downstream waters such as the Gulf of Mexico and Lake Winnipeg. Nutrient loads are affected by both nutrient concentrations and river flow.

The flow-adjusted loads show similar trends as the flow-adjusted concentrations. For example, when using flow-adjusted methods, data from the Mississippi River at Red Wing and Winona show phosphorus load decreases of 27 to 54%, respectively, varying with the assessed site and timeframe examined.

However, the non flow-adjusted loads show different results because precipitation and associated river flow has markedly increased during the past two decades in Southern and Eastern Minnesota. Decreasing phosphorus *concentrations* in these areas are not translating into statistically significant decreasing phosphorus *loads*. Phosphorus loads in the Mississippi River Basin have non-significant trends.

In the St. Louis River at Scanlon, flow-adjusted phosphorus loads decreased by 44% over 43 years. Decreasing phosphorus loads during the past 10 and 20-years were not statistically significant. The five-year rolling average of actual loads (non flow-adjusted) appear to be increasing since 2003, along with increasing precipitation during this same timeframe.

In the Red River, load results were only conducted using flow-adjusted approaches and the results parallel the concentration trend findings.

For nitrate, the combination of increasing concentrations and increasing flow has led to load increases of 62% on the Mississippi River near Red Wing. The non flow-adjusted nitrate loads at Red Wing increased by 62% with a combination of increasing river flow and increasing concentrations. Further downstream at Winona, there is too much variability for the flow-adjusted 20-year concentration or load trends to be statistically significant.

In the St. Louis River, the flow-adjusted nitrate load trends were not significant for short, medium and long-term loads. The five-year rolling average actual loads (non flow-adjusted loads) appear to be increasing since 2004.

References cited in Appendix C

Met Council (Metropolitan Council Environmental Services). 2018. Regional Assessment of River Water Quality in the Twin Cities Metropolitan Area (1976 – 2015). Metropolitan Council, Saint Paul, MN.

Nustad R.A., and Vecchia A.V.. 2020. Water-Quality Trends for Selected Sites and Constituents in the International Red River Basin, Minnesota and North Dakota, United States, and Manitoba, Canada, 1970-2017: U.S. Geological Survey Scientific Investigations Report 2020-5079, 75 p. https://doi.org/10.3133/sir20205079

Attachment A – MPCA Trend Analysis Methods

Methods written by James Jahnz (MPCA)

Trend Methods: Bootstrapped Seasonal Kendall Test

Simple directional trends were determined by applying a block bootstrap procedure to water quality samples collected at MPCA Watershed Pollutant Load Monitoring (WPLMN) sites. Subsamples were weighted to better represent the underlying flow regime, a flow correction was applied to each subsample, and the seasonal Kendall test was applied. A confidence interval for Kendall's Tau was created after 1,000 bootstrap replicates were created. This confidence interval was then used to determine significance of Kendall's Tau to a 90% degree of confidence. Nitrate+nitrite nitrogen and total phosphorus were analyzed in this way and reported for 10- and 20-year time periods. Below is a more comprehensive description of the above methodology.

All WPLMN monitoring locations designated as 'basin' or 'major watershed' sites were considered for analysis. The water quality record for each of these sites was then examined to meet the minimum data requirements for this study. Minimum data requirements are as follows.

1. Sample location must be currently active and monitored year-round under the WPLMN program.
2. Greater than 50% of water quality samples must show concentrations above the minimumreporting limit for each dataset analyzed.
3. Water quality record must not display any major gaps in water quality sampling or daily flow measurements.
4. The length of time from the first to last sample must be approximately 8 or more years for the 10-year analysis, 15 or more years for the 20-year analysis, and 35 or more years for the 40-year analysis.

Results were not reported for any site where the water quality record did not satisfy requirements for analysis. In cases where results met data requirements for at least one parameter, but not for all parameters at a given site, results were reported for the parameters with sufficient data only. Datasets in which long gaps occur were evaluated on a case-by-case basis, and sites determined to have greater than approximately two years of sparse or missing data were removed. In cases where water quality sampling had previously occurred at the same location, but under a different site ID, or a nearby location in which no major confluence occurs between sites, datasets were combined in order to create a continuous water quality record of sufficient length to satisfy minimum data requirements for 20-year and 40-year trend analysis. For the purpose of consistency, the same datasets were used for 10-year trend analysis.

The highest reporting limit (RL) among water quality samples censored due to low concentration was identified for each individual dataset prior to analysis. All water quality samples with reported concentrations below that value were then censored as though they were also reported below the highest reporting limit, and the reporting limit was treated as though it were the maximum reporting limit found in the dataset. This was done because multiple reporting limits can create a false signal that may result in detection of a trend where a trend does not exist, or failure to detect a trend where a trend exists.

Periods of 10, 20, and 40 years were analyzed and results are reported. The 40-year period begins January 1, 1978, the 20-year period begins on January 1, 1998 and the 10-year period begins on January 1, 2008. All time periods end on January 1, 2018.

Trend analysis was performed according to the following procedure:

1) Subsample the population of water quality samples by season.
2) Correct for flow.
3) Perform seasonal Kendall test and record Kendall's tau.
4) Repeat steps 1-3 1,000 times and build confidence interval of Kendall's tau.
5) Use confidence interval of Kendall's tau to determine significance.

Water quality records analyzed in this study were subsampled prior to analysis such that one sample per season was chosen for analysis and the rest were discarded. Seasons were designated as follows; Season 1 (January-March), Season 2 (April-June), Season 3 (July-September), and Season 4 (October-December).

WPLMN sampling collection protocol requires water samplers to collect three or more samples for each flow event (rising limb, peak flow, and falling limb samples). This results in a dataset that is optimized for load calculation, but not for trend analysis. Specifically, samples are not randomly collected and water quality sample datasets are at risk of over-representing high flow events, especially on the peak and rising limb of high flow events.

Subsampling was performed in an effort to transform subsampled datasets such that they more closely approximate a random sampling regime. For each season-year combination, a random day was chosen. The two water quality samples immediately preceding and immediately following the randomly chosen day were identified. Of those two water quality samples, the sample collected on the day with a flow value closest to the flow value observed on the randomly chosen day was selected for analysis, and the rest of the samples taken during that season were not included in the subsampled dataset. Using flow as a selecting factor instead of time alone takes advantage of the sampling regime described above along with general principles of concentration-flow relationships to select the water quality sample most similar to the randomly selected day with respect to timing and hydrology. This subsampling procedure effectively prevents event samples from being over-represented in the subsampled datasets that are analyzed for trend. This subsampling procedure also results in a subsampled dataset with homogenous sample frequency such that the final analysis weighs periods of high observation frequency and periods of low observation frequency equally. Samples reported as below RL or censored previously for being below the maximum RL were then assigned a random value between zero and the maximum RL.

Flow correction was performed by calculating the residuals of a moving average (LOWESS) line with a smoothing value of 2/3 (f=2/3) for the concentration flow relationship. This method was selected as a non-parametric alternative to calculating residuals of a linear regression, a common method used to correct for a third variable. Base R was used to calculate the LOWESS line.

The seasonal Kendall test was performed on the flow corrected dataset using the 'rkt' package in R and results were recorded. Seasons were defined as above. No covariable was defined; a flow correction was applied prior to performing the Kendall test.

The above steps were then repeated 1,000 times, and a confidence interval for Kendall's tau was built for each site. Sites for which a 90% confidence interval for Kendall's tau does not overlap with zero were determined to show a significant trend. The direction of significant trends were determined by the sign of the Kendall's tau in the confidence interval, a 90% confidence interval comprised of only positive values displays a positive trend, and a 90% confidence interval displaying only negative values displays a negative trend.

Trend Methods – WRTDS, EGRET, and EGRETci

MPCA pollutant load trends for major rivers and certain major watershed outlet sites were calculated using the EGRET and EGRETci packages available for R. Both packages were created by the USGS and are capable of producing an array of products, including annual loads and yearly average concentration estimates.

EGRET and EGRETci use a model called Weighted Regression on Time, Discharge, and Season (WRTDS). WRTDS uses pollutant concentration data and a complete daily flow record to create daily concentration and flux estimates, as well as yearly average concentration and load estimates and long-term trend estimates. It does this by applying a moving window approach such that water quality samples collected in close temporal proximity to a given day have a high degree of influence on the resulting pollutant concentration estimate, and water quality samples collected at a greater time step are weighted proportionally less until they are no longer within the moving window. Samples that fall outside of the moving window are given a weight of zero and do not influence the daily estimate in question. The same basic approach is applied to flow (water quality samples collected on days where flow was similar are heavily weighted and those collected on days where flows fall outside the moving window do not influence the daily estimate), and season (water quality samples collected on days around the same time of year are heavily weighted and those collected during a completely different time of year fall outside the moving window do not influence the daily estimate). WRTDS is designed to perform well with different water sampling regimes and changing water sampling regimes. See Hirsch et al (2010) for a comprehensive description of the WRTDS model.

EGRETci is an add-on package for EGRET that builds on the base package by applying a block bootstrap type approach in which the population of sample observations are resampled and the WRTDS model is applied many times until a confidence interval is built. This technique allows users to understand the range of uncertainty associated with yearly concentration and load estimates and calculate *p* values from which significance is determined. See Hirsch et al (2015) for a comprehensive description of the bootstrap technique used in EGRETci.

EGRET and EGRETci were originally made to work with at least 10 years of water sample concentration and daily flow data. The original workflow uses methodology designed to eliminate the influence of year-to-year variations in flow. Recent updates increase the minimum data requirements to 15 years and allow for the estimation of the influence of changing flow on changing pollutant concentrations and loads. The original workflow was used for this study.

Large river and outlet sites included in this study that were monitored by the MPCA were analyzed for nitrate+nitrite-nitrogen and total phosphorus using the original workflow for WRTDS and EGRETci. Periods of 10, 20, and 40 years were modeled individually using EGRETci and results are reported. The 40-year period begins January 1, 1978, the 20-year period begins on January 1, 1998 and the 10- year period begins on January 1, 2008. All time periods end on January 1, 2018. In cases where the period of record began during a dataset, the period of analysis was shortened such that the start date began immediately following the gap in the water quality sample record. Gaps in sample data consisting of two or more years of no samples or sparse samples were entered into EGRET and EGRETci prior to running WRTDS so that the model does not make estimates for periods that lack sufficient information to make realistic estimates. Confidence intervals were set to include 500 individual model runs from which confidence intervals were built, and confidence levels for trends were set at 90%.

References cited in Attachment A – MPCA Trend Analysis Methods

Carlstein, E. 1986. The use of subseries values for estimating the variance of a general statistic from a stationary sequence. The Annals of Statistics, 14(3): 1171-1179.

Cleveland, W.S. 1979. Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association 74(368): 829-836.

Dimitris, N.P., and Romano, P.R. 1994. Large sample confidence regions based on subsamples under minimal assumptions. The Annals of Statistics, 22(4): 2031-2050.

Hirsch, R.M., Archfield, S.A., and De Cicco, L.A. 2015. A bootstrap method for estimating uncertainty of water quality trends. Environmental Modelling & Software, 73: 148-166.

Hirsch, R.M., Moyer, D.L., and Archfield, S.A. 2010. Weighted regression on time, discharge, and season (WRTDS), with application to Chesapeake Bay inputs. Journal of the American Water Resources Association, 46(5): 857-880.

Lahiri, S.N., and Zhu,J. 2006. Resampling methods for spatial regression models under a class of stochastic designs. The Annals of Statistics 34(4): 1774-1813.

Marchetto, A., Rogora, M., and Arisci, S. 2013. Trend analysis of atmospheric deposition data: A comparison of statistical approaches. Atmospheric Environment, 64: 95-102.

Yue, S., and Pilon, P. 2004. A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection. Hydrological Sciences 49(1): 21-37.