C1. Nitrate Trends in Minnesota Rivers

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Objective

Regular sampling of river and stream water for nitrate began at numerous sites on Minnesota's rivers during the mid-1970s, and many of these sites continued to be monitored through 2008-2011. A few of these sites were previously assessed for nitrogen (N) load and concentration temporal trends, as is reported in Chapter C2. However, most sites have either not been assessed for nitrate trends or have been studied for trends using a shorter period of time and different statistical methods compared to this study.

The objective of this study was to assess long-term trends (30 to 35 years) of flow-adjusted concentrations of nitrite+nitrate-N (hereinafter referred to as nitrate) in a way that would allow us to discern changing trends. Recognizing that these trends are commonly different from one river to another river and from one part of the state to another, our objective was to examine as many river monitoring sites across the state as possible for which sufficient long term streamflow and concentration data were available.

The nitrate concentration parameter was chosen for trend analyses for the following reasons:

- Nitrate is the dominant form of N in most streams with elevated total nitrogen (TN) concentrations (see Chapter B2).
- Nitrate can have adverse human and aquatic-life impacts at high concentrations (see Chapter A2).
- Nitrate concentrations in Minnesota rivers and streams are mostly elevated as a result of human activities (see Chapter A2).
- The ammonia+ammonium form of N has been consistently shown in previous studies to have decreased substantially since the late 1970s (see Chapter C2), and no additional trend analysis of that N parameter was considered to be needed at this time.
- Fewer long-term data are available for TN as compared to nitrate.

Nitrate concentration trend analyses can be used to help us understand how human activities and other factors have affected stream nitrate over different time periods. One challenge, however when interpreting nitrate trend results, is a lag time that occurs between changes to the land and the corresponding change to stream N concentrations, especially where slow moving groundwater is a dominant contributor to streamflow and nitrate loads. In some areas, it can take many years for groundwater to move into surface water. In areas other areas where groundwater flow to streams is much quicker, such as tile-drained lands and karst lands, the land changes can affect stream water quality within a much shorter period of time.

Nitrate *load* trends were not assessed in this study because the monitoring frequency at most sites was insufficient for load-trend analyses, and most of the sites where load trends could be determined were already reported by Lafrancois et al. (2013) for the 1976-2005 time period (see Chapter C2).

Site selection

We targeted sites that had a long-term (pre-1980) nitrate monitoring record and associated streamflow records corresponding to the same timeframe. We avoided locations that were intentionally sited to evaluate upstream point sources. We also avoided sites where sampling was discontinued prior to 2008 or that had large gaps in the monitoring record.

The primary long-term data set available for Minnesota rivers is from sites known as "MPCA Minnesota Milestone" sites. MPCA Minnesota Milestone sites were used for 45 of the 51 sites analyzed for long-term trends (Table 1). Most of the MPCA Minnesota Milestone sites used for trend analyses had nitrate concentration data over a 30- to 35-year period. The MPCA Minnesota Milestone sites were typically sampled by MPCA staff 9-10 months per year by taking grab samples; yet occasionally the sampling frequency was reduced to 7-8 months during the year. With only a few exceptions, these sites were sampled every year for nitrate from the mid- to late-1970s until the mid-1990s, at which time the sampling frequency was reduced to two out of every five years, or 40% of the years. Sampling continued at these sites through 2008-2011 at the reduced frequency. All water quality data are stored in the Environmental Quality Information System (EQuiS).

We also conducted trend analyses on a second set of six monitoring sites. The six sites were sampled (grab samples) twice monthly every year since 1976 by the Metropolitan Council Environmental Services. In a few locations, we did not report trends at MPCA Minnesota Milestone sites that were located near the Metropolitan Council sites, but instead focused our efforts on the more robust long-term data sets obtained by the Metropolitan Council. Data are stored at the Metropolitan Council.

Our analysis of flow-adjusted trends included only those nitrate monitoring sites that could be paired with a nearby streamflow gauging station (U.S. Geological Survey, 2013) for which streamflow data were available for the same years as the nitrate data. The streamflow gauging stations were all within criteria used for other similar studies (e.g. Lorenz et al., 2009). Three sites (198, 003, 975) had nitrate monitoring data since the 1970s, but only had streamflow data since 1991-94. For those sites, our trend analyses began in the early 1990s and continued through 2010.

The location of all monitoring sites used for trend analyses is shown in Figure 1 and are listed along with the number of times each site was sampled in Table 1. The Metropolitan Council monitoring sites are denoted with an asterisk in the "Map Number" column in Table 1. The number of samples (observations) collected and used for trend analyses at the six Metropolitan Council monitoring sites range from 778 to 899 (Table 1). The number of samples is much lower for the MPCA Minnesota Milestone sites, which were typically sampled 200 to 300 times.

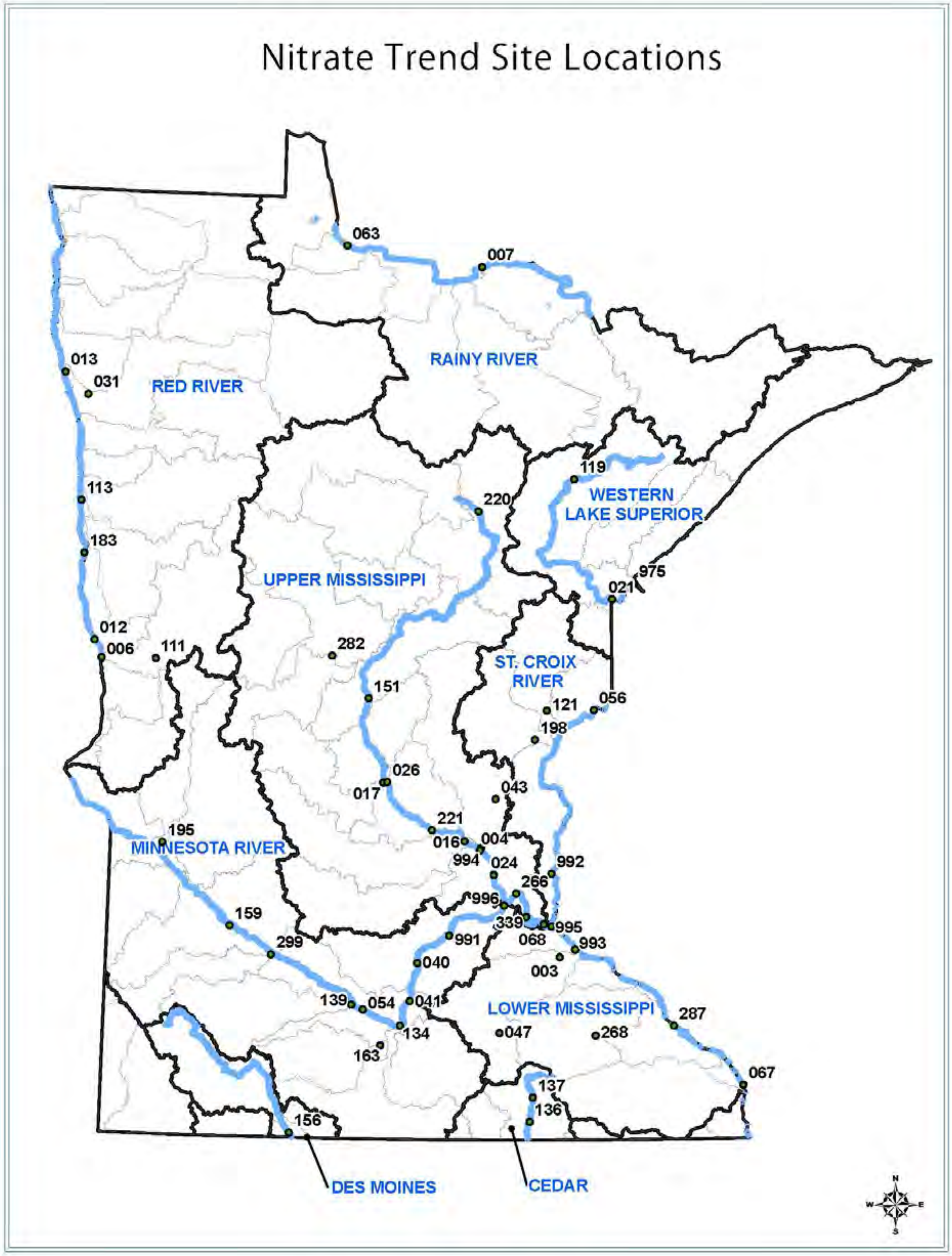


Figure 1. Site locations and associated site numbers for each of the river monitoring sites where trend analyses were completed (refer to Table 1 for more information about each site). Black lines are major basin drainage basin boundaries and blue lines are main stem rivers. Blue lettering refers to the major basin name.

Table 1. Nitrate monitoring site locations/numbers and associated number of observations (nitrate sampling events) and U.S. Geological Survey streamflow gauging station number. An asterisk indicates stations sampled by the Metropolitan Council. All other sites are MPCA Minnesota Milestone sites.

Site No. (Figure 1)	Location Code	Nitrate Monitoring Location	No. of Observations	Streamflow Gauging Station No.
Western Lake Superior Basin				
119	S000-119	St. Louis River, Forbes	223	04024000
021	S000-021	St. Louis River, Fond Du Lac	239	04024000
975	S003-975	St. Louis River Duluth	66	04024000
Red River of the North Basin				
111	S000-111	Otter Tail River, Fergus Falls	130	05046000
006	S000-006	Otter Tail River, Breckenridge	247	05046000
012	S000-012	Red River, Brushvale	348	05051000
183	S000-183	Red River, Moorhead	247	05054000
113	S000-113	Red River, Pearley	250	05064500
031	S000-031	Red Lake River, Fisher	211	05280000
013	S000-013	Red Lake River, East Grand Forks	244	05280000
Rainy River Basin				
007	S000-007	Rainy River, International Falls	250	05133500
063	S000-063	Rainy River, Baudette	254	05133500
Upper Mississippi River Basin				
220	S000-220	Mississippi River, Blackberry	288	05211000
282	S000-282	Long Prairie River, Motley	271	05245100
151	S000-151	Mississippi River, Camp Ripley	227	05267000
017	S000-017	Sauk River, Sauk Rapids	304	05270500
026	S000-026	Mississippi River, Sauk Rapids	244	05270700
221	S000-221	Mississippi River, Monticello	253	05288500
004	S000-004	Crow River, Dayton	152	05280000
994*	UM 871.6	Mississippi River, Anoka	841	05288500
043	S000-043	Rum River, Isanti	289	05286000
016	S000-016	Rum River, Anoka	112	05286000
024	S000-024	Mississippi River, Fridley	243	05288500
Minnesota River Basin				
195	S000-195	Pomme de Terre River, Appleton	316	05294000
159	S000-159	Yellow Medicine River, Granite Falls	145	05313500
299	S000-299	Redwood River, Redwood Falls	199	05316500

Site No. (Figure 1)	Location Code	Nitrate Monitoring Location	No. of Observations	Streamflow Gauging Station No.
139	S000-139	Cottonwood River, New Ulm	197	05317000
054	S000-054	Minnesota River Courtland	232	05325000
163	S000-163	Watonwan River, Garden City	282	05319500
134	S000-134	Blue Earth River, Mankato	313	05320000
041	S000-041	Minnesota River, St. Peter	226	05325000
040	S000-040	Minnesota River, Henderson	242	05330000
991*	MI 39.4	Minnesota River at Jordan	778	05330000
996*	MI 3.5	Minnesota River at Fort Snelling	915	05330000
Mississippi River between the Minnesota and St. Croix Rivers				
266	S000-266	Mississippi River, St. Paul Wabasha St.	332	05331000
339	S000-339	Mississippi River, Grey Cloud	329	05331580
068	S000-068	Mississippi River, Hastings Lock and Dam No. 2	179	05331580
St. Croix River Basin				
056	S000-056	St. Croix River, Danbury, WI	309	05333500
121	S000-121	Kettle River, Hinkley	291	05336700
198	S000-198	Snake River, Pine City	190	05338500
992*	SC 23.3	St. Croix River, Stillwater	896	05340500
995*	SC 0.3	St. Croix River, Prescott	899	05340500
Lower Mississippi River Basin				
993*	UM 796.9	Mississippi River, Prescott Lock and Dam No. 3	870	05331000
047	S000-047	Straight River, Clinton Falls	243	05353800
003	S000-003	Cannon River, Welch	107	05355200
268	S000-268	Zumbro River, South Fork, Rochester	241	05372995
287	S000-287	Mississippi River, Minneiska Lock and Dam No. 5	217	05378500
067	S000-067	Mississippi River, LaCrosse, WI	230	05378500
Cedar and Des Moines River Basins				
137	S000-137	Cedar River, Lansing	206	05457000
136	S000-136	Cedar River, Austin	300	05457000
156	S000-156	Des Moines River, West Fork, Petersburg	133	05476000

Statistical analysis methods

The long-term trends in flow-adjusted concentrations (FAC)s were assessed using the QWTREND program (Vecchia, 2003a, 2005). QWTREND was selected because it can describe long-term trends, not just monotonic trends; is insensitive to changes in the variability in streamflow; is also insensitive to unexplained variability in water quality (Lorenz et al., 2009); and it can be used to assess the relation between streamflow and water quality and sampling design. QWTREND uses a time-series model for estimating trends in FAC. The basic form of the model is:

FAC = Intercept + Time Series + Long Term + Intermediate Term + Seasonal + Trend + HFV,

where

FAC	is the log of the flow-adjusted concentration.
Intercept	is the intercept term.
Time Series	is the collection of autoregressive and moving-average time-series relations between streamflow and concentration and within the concentration data.
Long Term	is the 5-year anomaly (5-year moving average log of streamflow).
Intermediate Term	is the 1-year and seasonal (3-month) anomaly.
Seasonal	is the first- and second-order Fourier terms that describe seasonal variation.
Trend	is the user-supplied trend terms that explain long-term deviations not described by the previous terms.
HFV	is the high-frequency variability in the streamflow, which is the daily streamflow after the long- and intermediate-term anomalies have been removed.

Vecchia (2000) describes the estimation of the time-series parameters, and Vecchia (2003b) describes the computation of the anomalies.

The suggested minimum data criteria for QWTREND (Vecchia, 2000) are (1) minimum water-quality record length of 15 years, (2) average of at least 4 samples per year, (3) at least 10 samples within each quarter of the sampled years, (4) less than 10% censored data (i.e. nondetections), and (5) complete streamflow record for the water-quality record for the period of interest plus the preceding 5 years. These criteria were generally met, but exceptions were made for the preceding 5-year part of Criterion 5 when streamflow records were shorter than the water-quality record. Several sites in northern Minnesota had very low nitrate concentrations, often below detection limits, and Criterion 4 was relaxed for those sites. Aldo Vecchia (written communication, Dec 14, 2012) stated that QWTREND generally is accurate for the trend estimates with as much as 20% censored data, and possibly is accurate with as much as about 35% censored data in some cases. As the percentage of censored data increases, the trends become progressively less reliable—the magnitude of the slope is decreased and the associated probability values (p-values) become more significant. For analyses with more than 35% censored data, QWTREND should be considered only an exploratory tool (Aldo Vecchia, USGS, oral communication
December 14, 2012).

QWTREND was used to determine when changes in the trend during the analysis period (typically 1975–2010) were statistically significant. The critical p-value for a single trend was set at 0.10 compared to the no-trend model. To avoid extraneous trends, the critical p-value for a two-trend model was set at one-half the attained p-value for the single-trend model, the critical p-value for a three-trend model was set at one-third the attained p-value for the single-trend model, and so forth.

The Long Term, Intermediate Term, and High Frequency Variability (HFV) parameters of the model describe the relation between concentration and streamflow. The HFV parameter includes an average response and Fourier terms, the sine and cosine, which describe seasonal differences in the HFV response. Only the average response was included in this analysis. The Long and Intermediate Terms describe the effects of sustained long- and short-term above or below average precipitation; positive parameters indicate a flushing process, negative values indicate a dilution effect, and a value near zero indicates no effect. The HFV parameter, in general, describes the effect of rainfall or snowmelt events. Again positive parameters indicate a flushing process, negative values indicate a dilution effect, and a value near zero indicates no effect. Only sites with less than 25% censored data were used in the analysis of concentration and streamflow.

Nitrate concentration trends across the state

An overview of the results is first described for main-stem rivers across the state, including the Red River, Minnesota River, Mississippi River, St. Croix River, Cedar River, Des Moines River, and St. Louis River (within the Western Lake Superior Basin). The statewide overview is followed by a more detailed description and discussion of the results for each major basin, including results for many tributary rivers within the basins.

Statistically significant ($p < 0.1$) trends in overall flow-adjusted nitrate concentrations mostly over the time period between the mid-1970s and the 2008-2011 timeframe (typically 1976-2010) are shown in Figure 2 for Minnesota's main-stem rivers. The magnitude of change over this time period was found to vary greatly across the state. Many (22 of 32) main-stem river sites showed upward trends (increased concentrations), ranging from 7% to 268% over the entire analysis time period (30 to 35 years at most sites). Four sites showed slight overall downward trends (decreased concentrations): the two most downstream sites on the Minnesota River, the most upstream site on the St. Croix River, and the most upstream site on the St. Louis River. Six sites showed no statistically significant change.

Because the nitrate concentrations are low in the Upper Mississippi River, Rainy River, and St. Louis River, even a very small addition of nitrate over time will result in a relatively high percentage increase. The large percentage increases in the Upper Mississippi River represent a nitrate concentration increase of 0.1 to 0.4 milligrams per liter (mg/l) (see tables 2-16, ending concentration for more context on understanding the percent change over time).

A commonly asked question is how nitrate concentrations have been changing over more recent years. Results for the most recent years for each main-stem river monitoring site are shown in Figure 3. The number of years encompassing these recent trends varies greatly, and was from 5 to 9 years at seven sites, and 10 years or more at all other sites. The results for these recent periods vary from one part of the state to another. In most northern Minnesota main-stem rivers, nitrate concentrations did not have a statistically significant trend in recent years, with a few exceptions, most notably an average 2% per year increase in the St. Louis River (Duluth) over the past 17 years. Upward trends during recent periods were indicated for the Cedar River and for most of the Mississippi River sites south of Sauk Rapids, with the recent rate of change at most sites comparable to the change over the complete period of record. Downward trends during recent years were indicated for some sites on the Minnesota River.

Long-term and recent nitrate concentration trends in several major tributaries to main-stem rivers were also assessed and mapped (Figures 4 and 5). Over the entire period of analysis, 11 different tributary rivers had nitrate concentration increases, and 3 of those rivers had two monitoring sites on the same river that both indicated increases. Four tributaries had no significant trend, and 1 tributary with two sites (Cannon River Watershed) had nitrate concentration decreases (Figure 4).

For the recent trend analyses, 5 tributaries showed upward trends, 5 tributaries had downward trends, and 7 tributaries had no statistically significant trend (Figure 5). Several tributary rivers have shifted from long-term upward trends (Figure 4) to downward and non-significant trends in recent years (Figure 5).

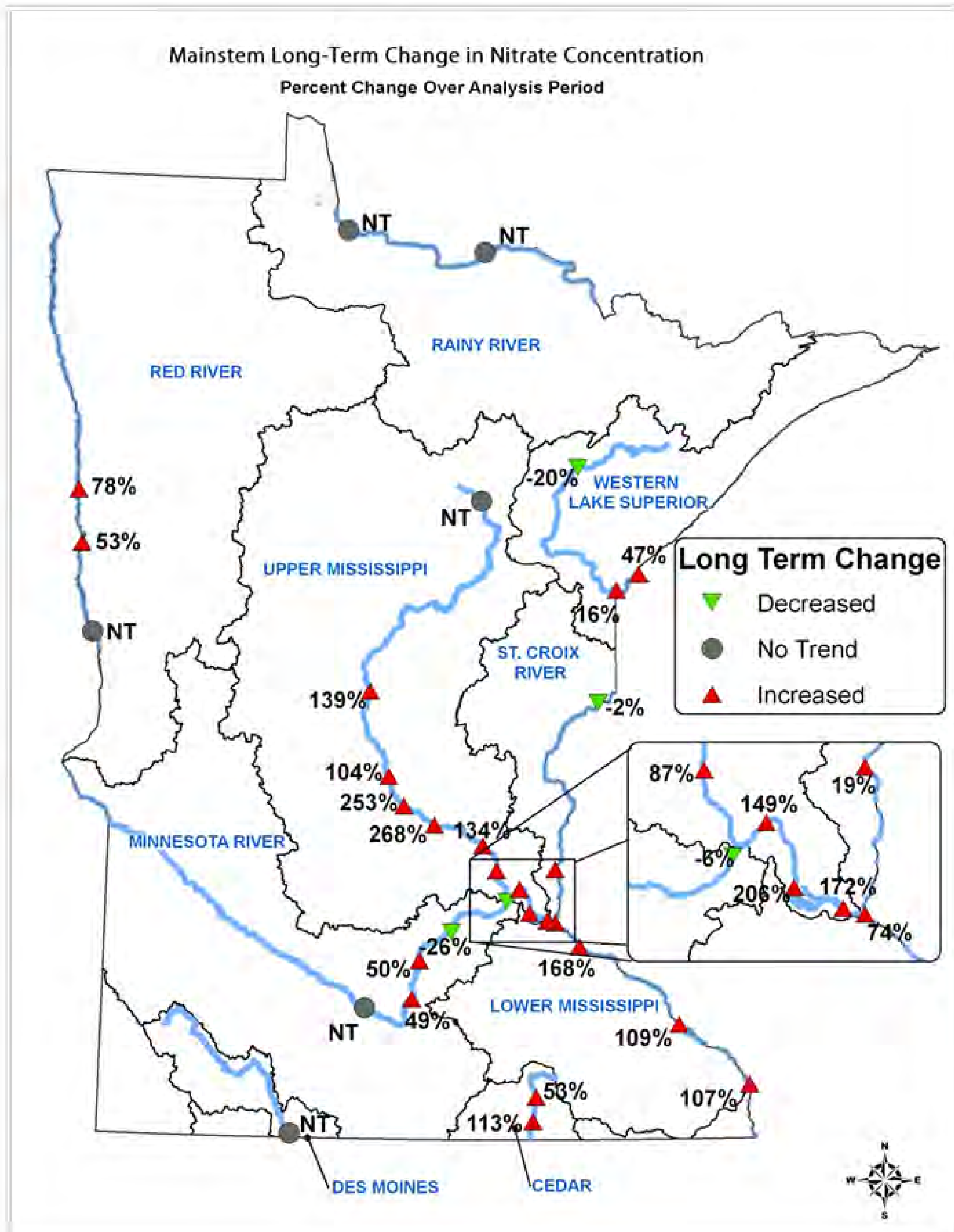


Figure 2. Mainstem river changes in nitrate concentration for main-stem rivers during the entire period of analysis, which was typically 1976 to 2010, but varied by site (see also tables 2 to 16). Values are the average percent change per year in nitrate concentrations over the analysis period. Major basins names are blue.

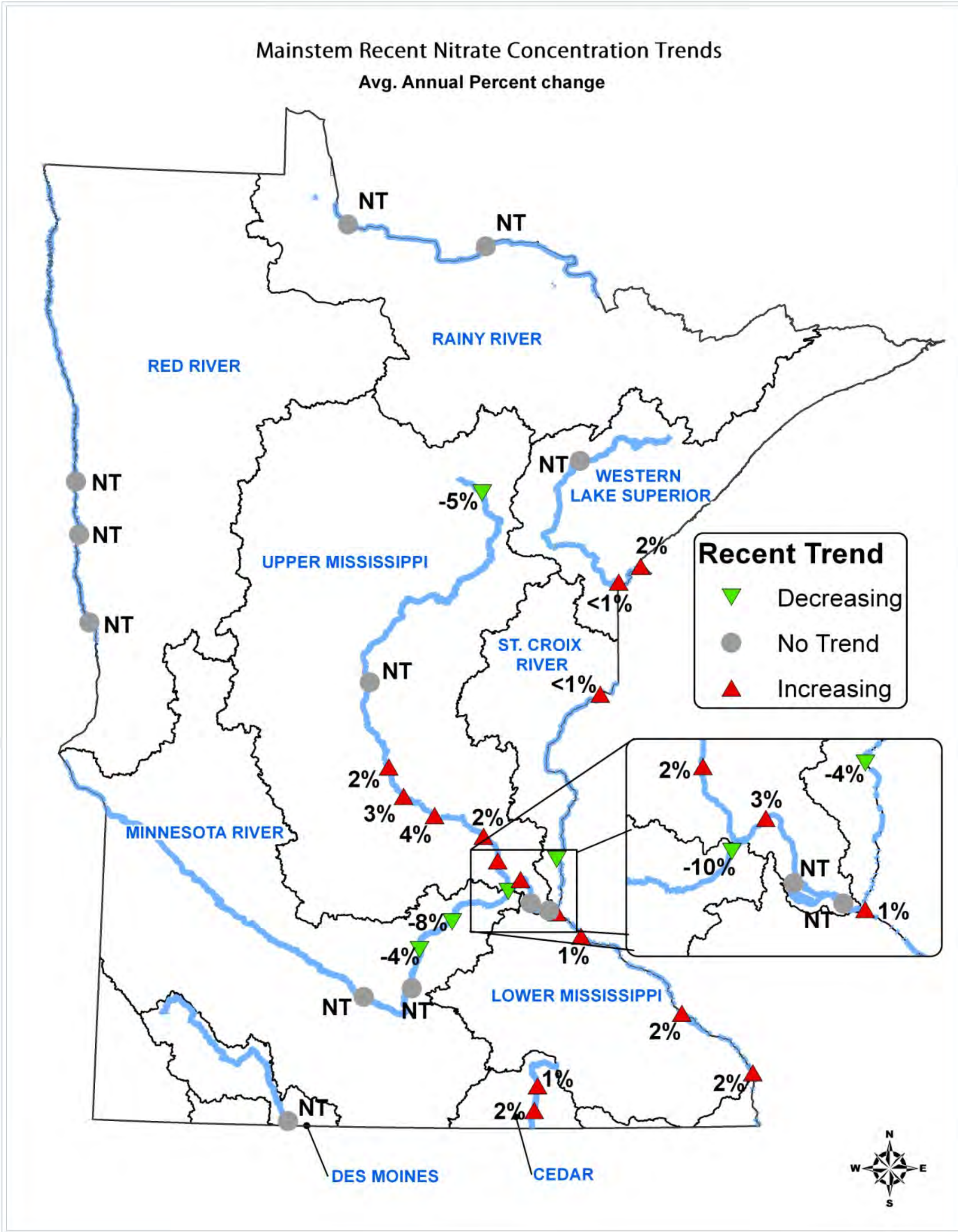


Figure 3. Trends in nitrate concentrations within past 5-15 years (ending in 2010 for most sites) for main-stem rivers. Values are the average percent change per year in nitrate concentrations during the most recent trend period. "Decreasing" indicates a downward trend and "increasing" indicates an upward trend. Major basins names are in blue lettering.

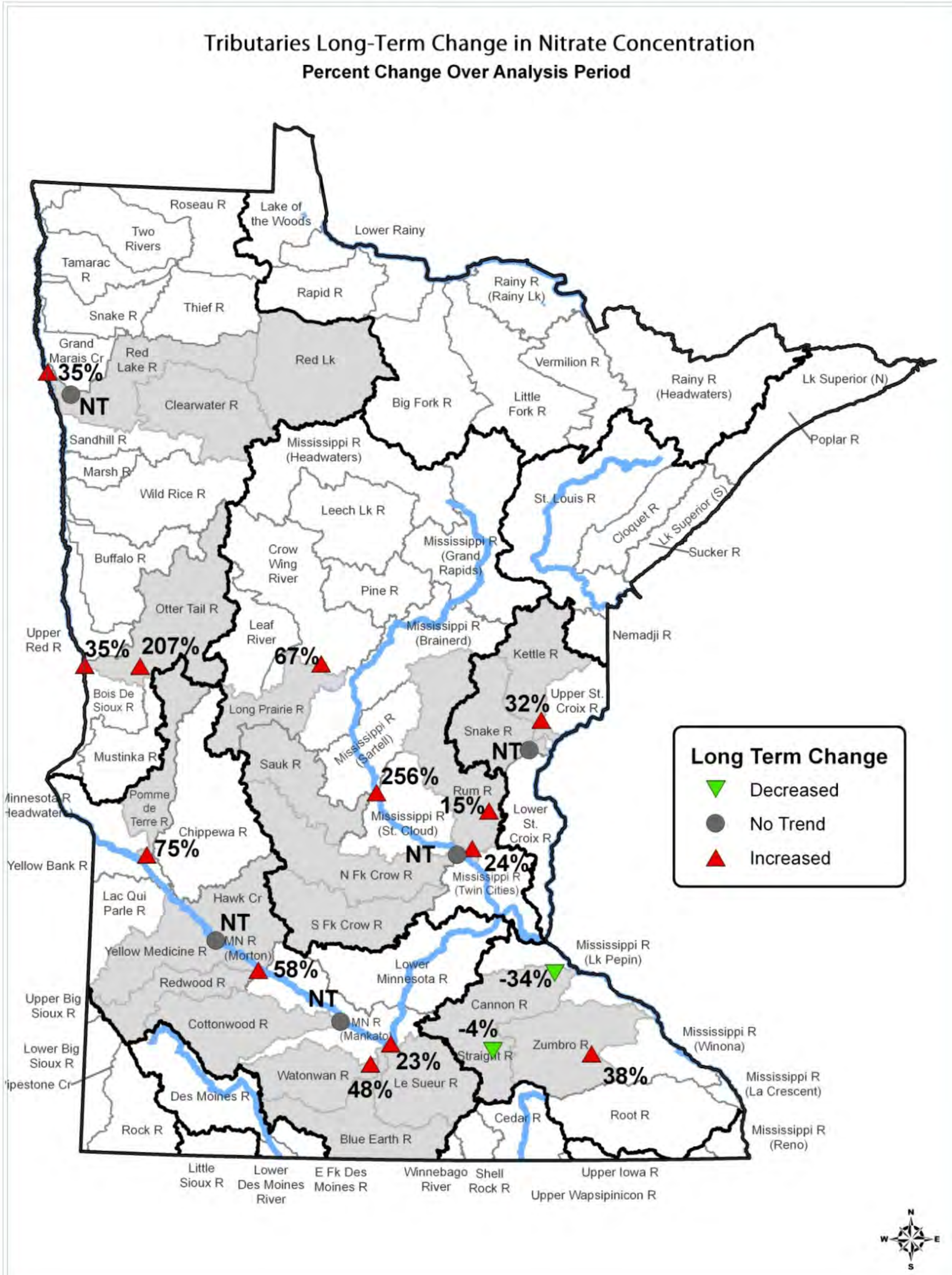


Figure 4. Percent change in nitrate concentrations in tributary rivers during the entire period of analysis (typically 1976 to 2010, but varied by site - see Tables 2 to 16). Values are the average percent change per year in nitrate concentrations over the analysis period. Watersheds associated with the trend analyses are shaded in gray.

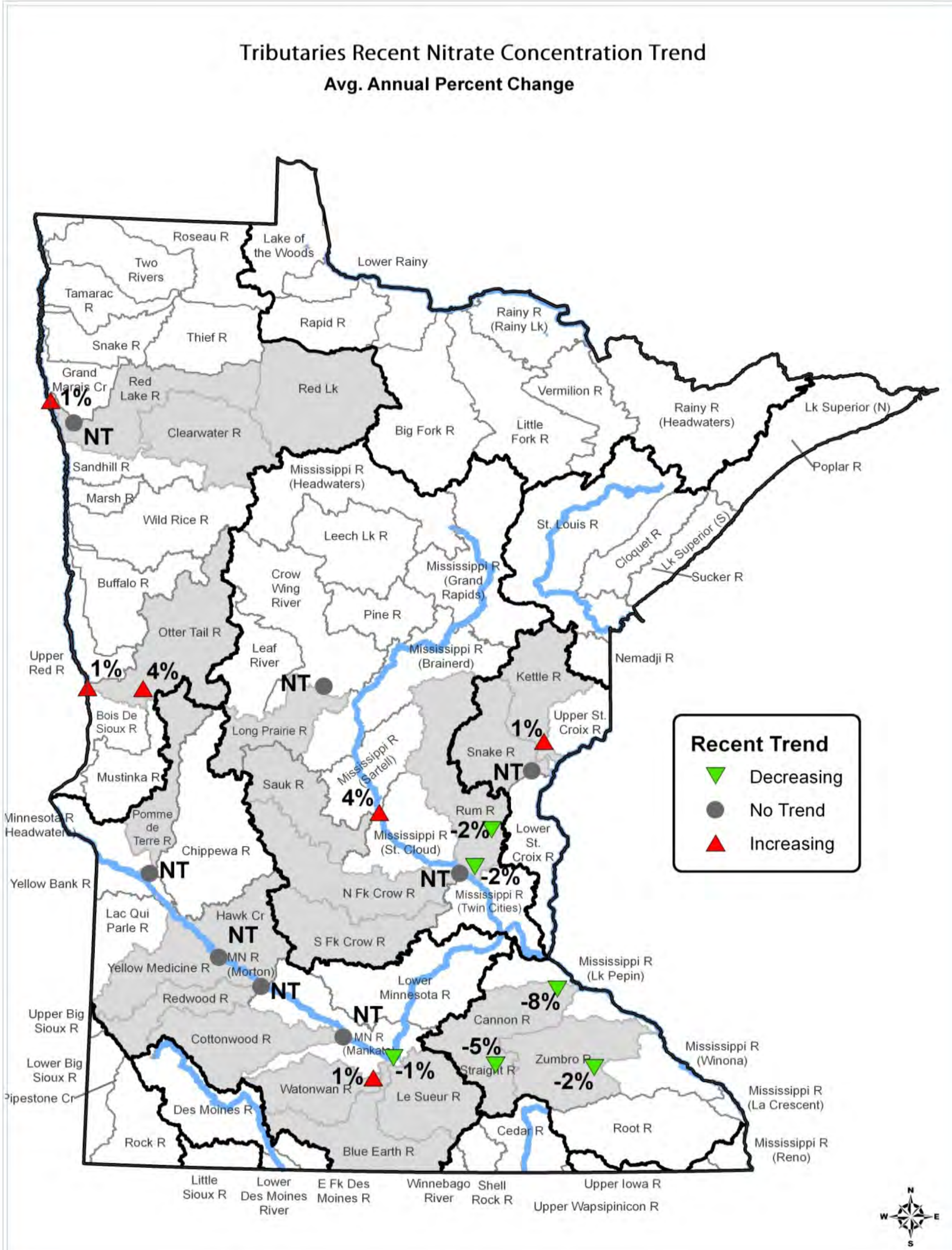


Figure 5. Trends in nitrate concentration for tributary rivers within the past 5-15 years (period ending in 2010 at most sites). Values are the percent change per year in nitrate concentrations during the most recent trend period. Watersheds associated with the trend analyses are shaded in gray. "Decreasing" indicates a downward trend and "increasing" indicates an upward trend.

At many sites, the long-term trends were not constant over the years. Some river sites had separate periods of upward, downward, or no trends. Therefore, we reported how the trends shifted throughout the 30- to 35-year period of analysis. The next section provides the results of how trends changed during the analysis period at each assessed monitoring site.

Nitrate concentration trends by basin

Trends in flow-adjusted nitrate concentrations are shown for main-stem rivers and tributaries analyzed in each major river basin (Tables 2 to 16). Note that for each site, an overall trend result is presented that represents a calculated change based on all statistically significant trends from the beginning of the trend analysis period to the end. Where trends for specific periods within the overall trend were found to be statistically significant, those specific trend segments are reported below the overall trend. A positive change represents a typical concentration at the end of the analysis period (2008-11) that is larger than the typical concentration for the site at the beginning of the analysis period, and a negative change represents a concentration that is less at the end of the analysis period than the typical concentration for the site at the beginning of the analysis period. "No trend" indicates that the trend was not statistically significant at the $p<0.1$ significance level.

Note that for two or more separate upward or downward trend segments, the sum of these segmented trends will not add up to the overall trend. This is because the percentage of increase or decrease is reported as an increase or decrease from the start of the segment, rather than the start of the entire period of analysis. For example, if a site starts with a concentration of 1 mg/l and the first decade has a 100% increase, then the concentration at the end of the first decade is 2 mg/l. If the trend during the second decade is a 25% increase, then the concentration will have increased from 2 mg/l to 2.5 mg/l. Therefore the overall increase over the two decades is 1.5 mg/l or 150% (not the sum of the 100% and 25% increases).

The "NO_3" concentrations in the graphs and the "ending concentration" in Tables 2 to 16 are annual average "nitrite+nitrate-N" concentrations during the last year of the statistical trend analysis. Because of the way the QWTREND model works, these concentrations represent an annual mean of the log of nitrite+nitrate-N concentrations, corrected for seasonal and streamflow variability, which were then translated back into a raw concentration. Therefore, for sites with a high degree of variation in nitrate concentrations from season to season, the concentrations reported in the tables and associated graphs are lower than either a flow-weighted mean concentration or an annual arithmetic mean concentration. These concentrations are therefore not comparable to concentrations reported in Section B of this report. Note also that different y-axis nitrate concentration scales are used in the trend graphics depending on the magnitude of concentrations, typically 0 to 1.0 mg/l and 0 to 10 mg/l.

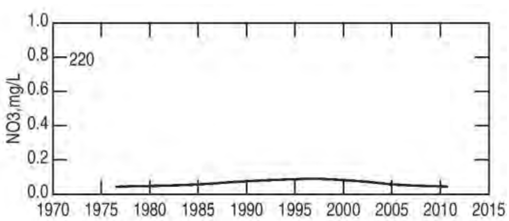
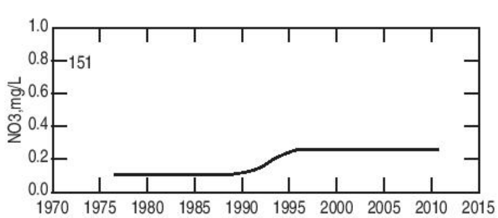
To find the location of specific site names noted below (often nearby city names), identify the associated site number in Tables 2 to 16 (left column), and refer to Figure 1. Some secondary site numbers in Tables 2 to 16 are in parentheses and indicate a Metropolitan Council monitoring site with their associated site number based on the river mile (distance upstream from the river mouth) at the sampling location.

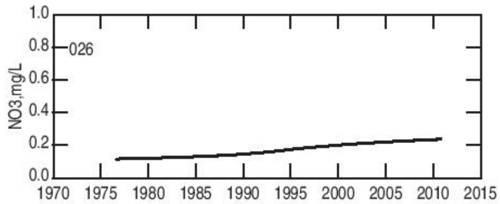
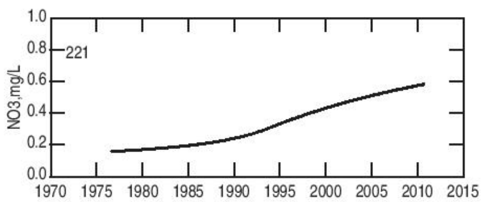
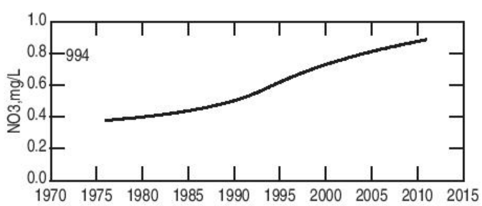
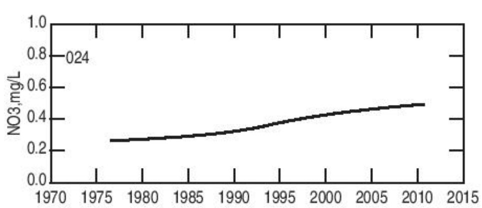
Mississippi River Basin results

Upper Mississippi River main stem (Blackberry to Fridley)

The general patterns in the Upper Mississippi River Basin are long-term increases in nitrate concentrations, with flow-adjusted concentrations often more than doubling over the three and a half decades of measurement (Table 2). The only exception to the long-term increase is the upstream-most Mississippi River site at Blackberry, which showed a decrease between 1997 and 2010. Recent period average annual increases range between 2% and 4% at all Mississippi River sites from Camp Ripley southward to Fridley. At the four most downstream sites, at Sauk Rapids, Monticello, Anoka, and Fridley, the trends were continuously upward since 1976.

Table 2. Trends in flow-adjusted nitrate concentrations in the Upper Mississippi River between the most upstream site at Blackberry to the most downstream site at Fridley. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1. A 0% change is a change which rounded off to 0% overall change (the increase during the first 22 years is nearly balanced by the decrease in the last 14 years; yet the increase and decrease were each statistically significant).

Site No.	Upper Mississippi River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
220	**Mississippi River – Blackberry**		0.05
	Overall change 1976-2010	*0%	
	1976 - 1997	+106%	
	1997 – 2010	-51%	
			
151	**Mississippi River – Camp Ripley**		0.26
	Overall change 1976-2010	+139%	
	1976-1988	NT	
	1989-1995	+139%	
	1996-2010	NT	
			

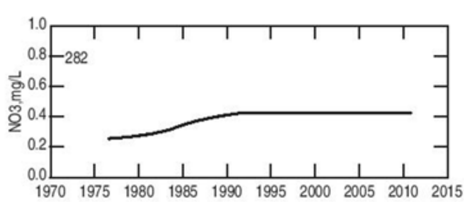
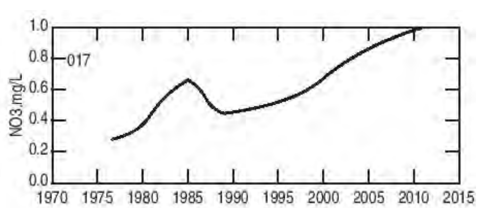
Site No.	Upper Mississippi River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
026	**Mississippi River – Sauk Rapids**		0.23
	Overall change 1976-2010	+104%	
			
221	**Mississippi River – Monticello**		0.58
	Overall change 1976-2010	+268%	
			
994(871.6)	**Mississippi River – Anoka**		0.88
	Overall change 1976-2010	+134%	
			
024	**Mississippi River – Fridley**		0.49
	Overall change 1976-2010	+87%	
			

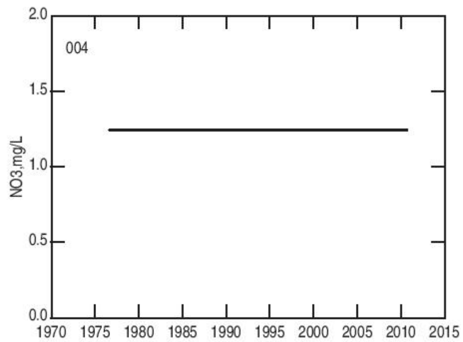
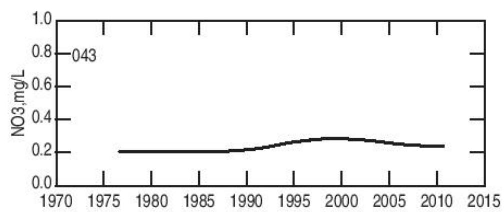
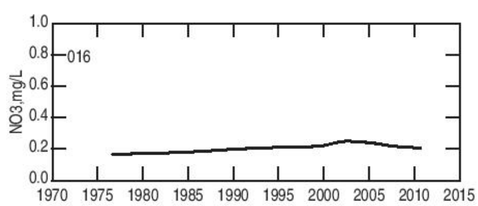
Tributaries of the Upper Mississippi River

Many tributaries flow into the Upper Mississippi River. Trends in all tributaries, along with trends in point source discharges and groundwater base flow discharging directly into the Mississippi River, affect the Mississippi River trends. Trends in four major tributaries were analyzed for this study. Three of the four tributaries showed an overall increase since 1976 and one tributary (Crow River) had no trend (Table 3). The nature of the increases was different in all three tributaries, with different magnitudes of increases (from 15 to 256%) and different periods of time when these increases occurred. During the past decade, the Long Prairie and Crow Rivers had no trend, while nitrate concentrations increased in the Sauk River and decreased in the Rum River.

The Sauk River is the only analyzed tributary that had a continuously upward trend in the past two decades, as was also found in the Mississippi River at Sauk Rapids, Monticello, Anoka, and Fridley. We were not able to assess the trend results in the many other tributaries to the upper Mississippi River due to a lack of sufficient monitoring data, and it is possible that those other tributaries also contributed to the upward trends in the Mississippi River.

Table 3. Trends in flow-adjusted nitrate concentrations in four tributaries of the Upper Mississippi River. The Rum River had two monitoring sites at different points along the river. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Tributaries - Upper Mississippi River Basin Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
282	**Long Prairie River – south of Motley**		0.43
	Overall change 1976-2010	+67%	
	1976-1991	+67%	
	1992-2010	NT	
			
017	**Sauk River - Sauk Rapids**		0.98
	Overall change 1976-2010	+256%	
	1976-1984	+137%	
	1985-1988	-33%	
	1989-2010	+123	
			

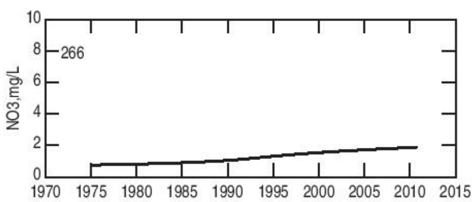
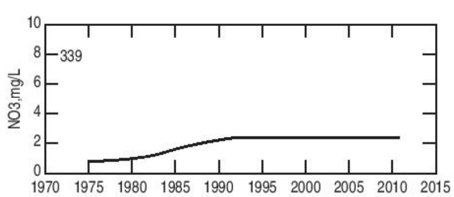
Site No.	Tributaries - Upper Mississippi River Basin Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
004	**Crow River – Dayton**		1.24
	Overall change 1976-2010	NT	
Note: y-scale 0-2 mg/l			
043	**Rum River - Isanti**		0.24
	Overall change 1976-2010	+15%	
	1976-1986	NT	
	1987-1998	+40%	
	1999-2010	-18%	
			
016	**Rum River - Anoka**		0.21
	Overall change 1976-2010	+24%	
	1976-1998	+29%	
	1999-2002	+16%	
	2002-2010	-18%	
			

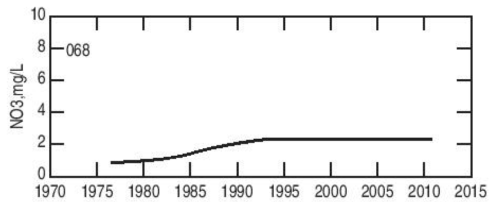
Mississippi River between the Minnesota and St. Croix Rivers

The three sites in the St. Paul area between the Upper and Lower Mississippi River Basins all had an overall increase in flow-adjusted nitrate concentrations over the entire period of record. However, the increases have largely diminished in recent years, with no apparent trend over the last two decades at the two most downstream sites (Table 4).

The Minnesota River, which merges with the Mississippi River upstream from these three sites, affects both the concentrations and trends at these three sites. The nitrate concentrations are substantially higher at these three locations on the Mississippi River, as compared to upstream Mississippi River sites at Anoka and Monticello. Another potential influence on nitrate concentrations in these segments of the Mississippi River is discharge from the Metro wastewater treatment facility between sites 266 and 339. This facility services much of the Twin Cities Metropolitan Area.

Table 4. Trends in flow-adjusted nitrate concentrations in the Mississippi River between its confluence with the Minnesota River and its confluence with the St. Croix River in the St. Paul area. A positive change in nitrate concentration represents a statistically significant ($p<0.1$) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant ($p<0.1$). Site No. refers to site location on Figure 1 and Table 1.

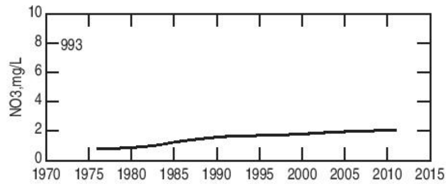
Site No.	Mississippi River – St. Paul Area Site Location / Trend Analysis Periods	% Change in Nitrate Concentrations	Ending Concentration, mg/l
266	**Mississippi River – St. Paul Wabasha St.**		1.9
	Overall change 1975-2010	+149%	
Note: Y-scale 0-10			
339	**Mississippi River – Grey Cloud Island**		2.4
	Overall change 1975-2010	+206%	
	1975-1991	+206%	
	1992-2010	NT	
			

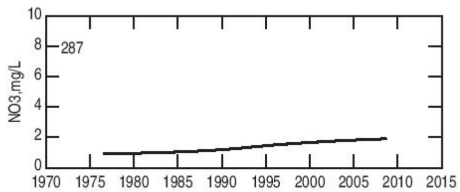
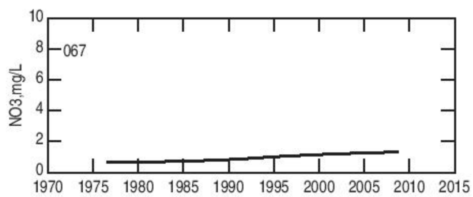
Site No.	Mississippi River – St. Paul Area Site Location / Trend Analysis Periods	% Change in Nitrate Concentrations	Ending Concentration, mg/l
068	**Mississippi River – Hastings Lock and Dam No. 2**		2.3
	Overall change 1976-2011	+172%	
	1976-1993	+172%	
	1994-2011	NT	
			

Lower Mississippi River - between Prescott (confluence with St. Croix River) and the Iowa border

In the Mississippi River between the Twin Cities and Iowa, flow-adjusted nitrate concentrations more than doubled since 1976, based on monitoring near Red Wing, Minneiska, and LaCrosse (Table 5). During the last two decades, concentrations had a reduced rate of increase at Prescott (Lock and Dam No. 3) where we have had continuous and more frequent monitoring (Table 1), but had a constant rate of increase farther downstream in Minneiska and LaCrosse.

Table 5. Trends in flow-adjusted nitrate concentrations in the Lower Mississippi River between its confluence with the St. Croix River and the Iowa border. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

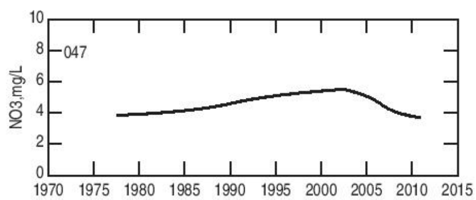
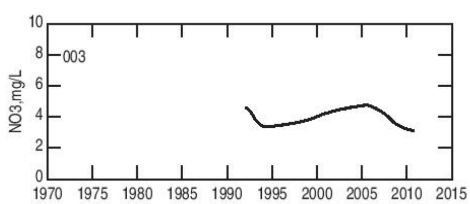
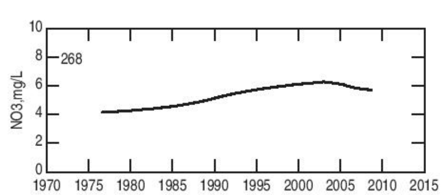
Site No.	Lower Mississippi River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
993	**Mississippi River – Prescott Lock and Dam No. 3**		2.1
	Overall change 1976-2010	+168%	
	1976 - 1991	+117%	
	1992-2010	+24%	
			

Site No.	Lower Mississippi River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
287	**Mississippi River – Minneiska Lock and Dam No. 5**		1.9
	Overall change 1976-2008	+109%	
			
067	**Mississippi River – LaCrosse, WI**		1.3
	Overall change 1976-2008	+107%	
			

Tributaries of the Lower Mississippi River

The three tributaries analyzed for trends in the Lower Mississippi River Basin all had downward trends in flow-adjusted nitrate concentrations between about 2003-05 and 2010 (Table 6). During the decade prior to that, all three sites had upward trends. Since 1976, the overall change in the Zumbro River has been a 38% increase. The Straight River had periods of increases and decreases, which have amounted to virtually no overall change (-4%). Many tributaries to the Lower Mississippi River from both the Minnesota and Wisconsin side of the basin were not analyzed for trends because the combination of flow and monitoring data were not available.

Table 6. Trends in flow-adjusted nitrate concentrations in four tributaries of the Lower Mississippi River. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Tributaries - Lower Mississippi River Basin Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
047	**Straight River – Clinton Falls**		3.8
	Overall change 1977-2010	-4%	
	1977-2002	+43%	
	2003-2010	-33%	
			
003	**Cannon River - Welch**		3.2
	Overall change 1991-2010	-34%	
	1991-1994	-29%	
	1994-2005	+42%	
	2005-2010	-35%	
			
268	**Zumbro River - Rochester**		5.71
	Overall change 1976-2008	+38%	
	1976-2002	+51%	
	2003-2008	-9%	
			

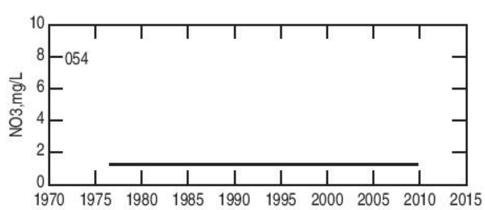
Minnesota River Basin results

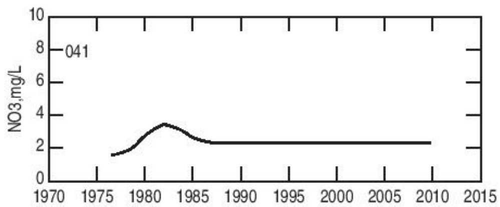
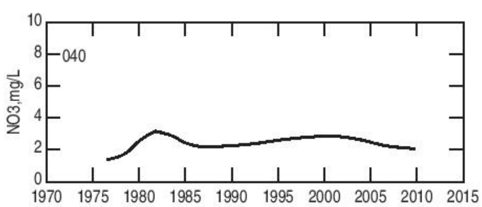
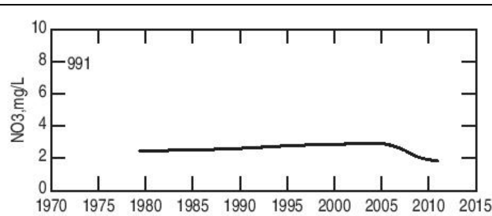
Minnesota River

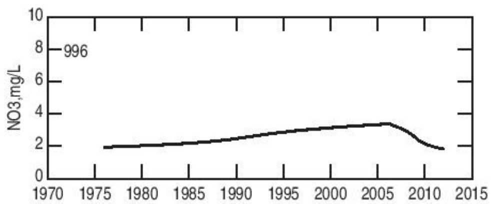
The nitrate trend analyses for Minnesota River sites indicated that flow-adjusted concentrations gradually increased in the Minnesota River for many years, but that there is evidence of amelioration in that trend in more recent years. In particular, the sites at Jordan and Fort Snelling, with the most extensive data sets (Table 1), had decreases of about 40% over the most recent six years ending in 2010 and 2011, respectively (Table 7).

Sites meeting the long-term trend analysis criteria were not available for the upper one-half of the Minnesota River main stem. The most upstream site analyzed is near Courtland, Minnesota, which is just southeast of New Ulm. At Courtland, where nitrate concentrations are still relatively low compared to downstream sites, trends in flow-adjusted nitrate concentrations were not found to be statistically significant (Table 7). Between Courtland and St. Peter, the influential tributaries of the Blue Earth, LeSueur and the Watonwan Rivers enter the Minnesota River. At St. Peter and Henderson, concentrations increased from 1976 to 1981 and then decreased from 1982 to 1986, followed by a more stable period of no significant trend at St. Peter and gradual upward and downward trends at Henderson. Farther downstream, in Jordan and Fort Snelling, the Minnesota River had upward trends from 1976 until 2004-05, followed by such large decreases that the overall change since 1976 is a slight reduction in flow-adjusted nitrate concentrations.

Table 7. Trends in flow-adjusted nitrate concentrations at five Minnesota River monitoring locations. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Minnesota River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
054	**Minnesota River - Courtland**		1.3
	Overall change 1976-2009	NT	
			

Site No.	Minnesota River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
041	**Minnesota River – St. Peter**		2.3
	Overall change 1976-2009	+49%	
	1976-1981	+119	
	1982-1986	-32%	
	1987-2009	NT	
			
040	**Minnesota River - Henderson**		2.1
	Overall change 1976-2009	+50%	
	1976-1981	+129%	
	1982-1986	-31%	
	1987-2000	+33%	
	2001-2009	-28%	
			
991(39.4)	**Minnesota River - Jordan**		1.9
	Overall change 1979-2010	-26%	
	1979-2004	+19%	
	2005-2010	-38%	
			

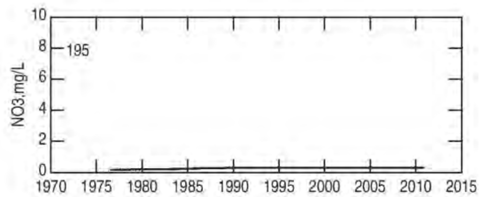
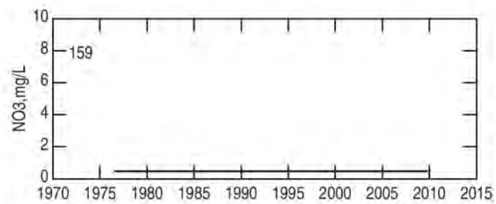
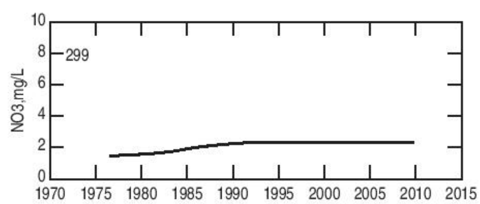
Site No.	Minnesota River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
996(3.5)	**Minnesota River – Fort Snelling**		2.2
	Overall change 1976-2011	-6%	
	1976-2005	+74%	
	2006-2011	-46%	
			

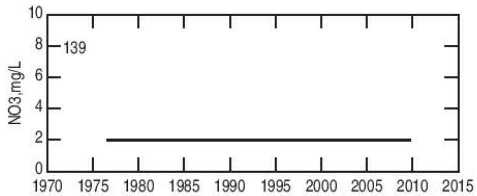
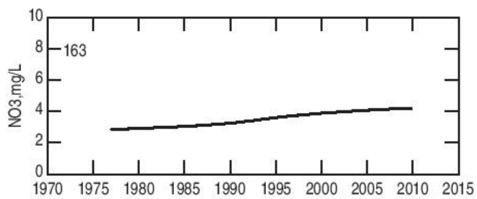
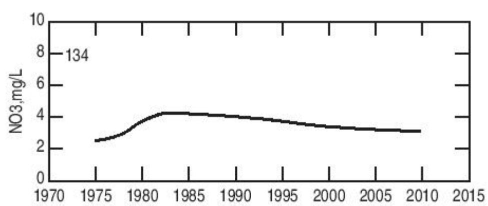
Tributaries to the Minnesota River

Trend analyses were performed for four tributaries to the Minnesota River upstream from Courtland (sites 195, 159, 299, 139). All four tributaries had gradual trends in flow-adjusted nitrate concentrations since 1993 (Table 8), and no significant trend was determined for 1993-2010 and 1992-2010 in the Pomme de Terre and Redwood Rivers. Prior to 1993, nitrate concentrations were increasing in the Pomme de Terre and Redwood Rivers and stable in the Yellow Medicine and Cottonwood Rivers.

The Blue Earth River contributes substantial quantities of nitrate to the Minnesota River and therefore has a large effect on nitrate concentrations in the Minnesota River. The Blue Earth River had an increase in nitrate concentrations from 1975 to 1982, followed by a long gradual decrease. Conversely, the Watonwan River had a long gradual increase in flow-adjusted nitrate concentrations. Neither of these trends in the Blue Earth and Watonwan mirrors the trends in the downstream segments of the Minnesota River, indicating that streamflow and nitrate inputs from additional tributaries have affected nitrate concentration trends in the lower Minnesota River.

Table 8. Trends in flow-adjusted nitrate concentrations in six tributaries of the Minnesota River. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Minnesota River Tributaries Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
195	**Pomme de Terre River - Appleton**		0.3
	Overall change 1976-2010	+75%	
	1976 – 1992	+75%	
	1993 – 2010	NT	
			
159	**Yellow Medicine – Granite Falls**		0.5
	Overall change 1976-2009	NT	
			
299	**Redwood River – Redwood Falls**		2.3
	Overall change 1976-2009	+58%	
	1976-1992	+58%	
	1992-2009	NT	
			

Site No.	Minnesota River Tributaries Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
139	**Cottonwood River – New Ulm**		2.0
	Overall change 1976-2009	NT	
			
163	**Watonwan River – Garden City**		4.2
	Overall change 1976-2009	+48%	
			
134	**Blue Earth River – Mankato**		3.1
	Overall change 1976-2010	+23%	
	1975-1982	+70%	
	1982-2009	-27%	
			

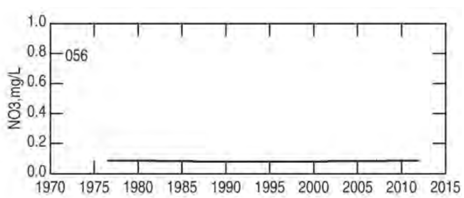
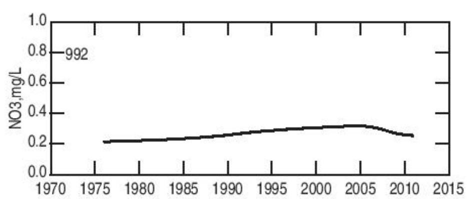
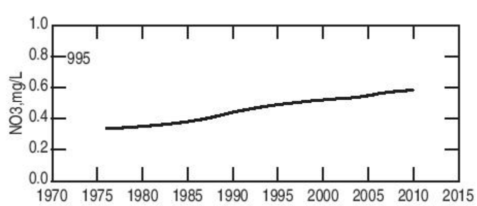
St. Croix River Basin results

St. Croix River

Changes in flow-adjusted nitrate concentrations were very minor at Danbury, Wisconsin, the upper-most monitored reach of the St. Croix River, remaining very low (less than 0.1 mg/l) throughout the period of record. Nitrate concentrations remain low throughout the St. Croix River, but are higher at Stillwater and Prescott, as compared to Danbury.

Farther downstream at Stillwater and Prescott, nitrate concentrations steadily increased from 1976 to 2005, at which time concentrations began to decrease at Stillwater and continued to increase at Prescott (Table 9).

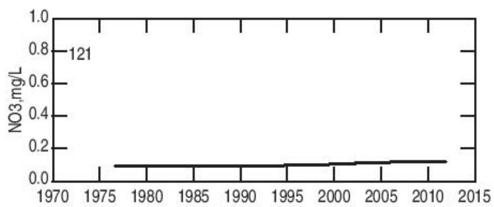
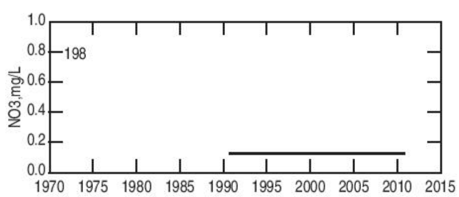
Table 9. Trends in flow-adjusted nitrate concentrations at three monitoring sites along the St. Croix River. "LS" indicates a lower strength trend. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	St. Croix River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
056	**St. Croix River – Danbury, WI**		0.09
	Overall change 1975-2011	-2%	
	1976-1992	-10%	
	1993-2011	+9%	
			
992/23.3	**St. Croix River - Stillwater**		0.26
	Overall change 1976-2010	+19%	
	1976-2004	+49%	
	2005-2010	-20%	
			
995(0.3)	**St. Croix River - Prescott**		0.58
	Overall change 1976-2009	+74%	
	1976-2000	+57%	
	2001-2009	+11%	
			

Tributaries to the St. Croix River

Flow-adjusted nitrate concentrations for two tributaries in the upper reaches of the St. Croix River were analyzed for trends. Both the Snake River and Kettle River have very low nitrate concentrations, around 0.1 mg/l, similar to the concentrations in the St. Croix River at Danbury. Nitrate concentrations in the Kettle River had no trend prior to 1990 and then started to gradually increase after 1991. The Snake River had no significant trends since 1991 (Table 10). Prior to 1991, streamflow data were not available for the Snake River to allow for flow-adjusted trend analysis.

Table 10. Trends in flow-adjusted nitrate concentration in two tributaries of the St. Croix River. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Tributaries – St. Croix River Basin Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
121	**Kettle River – Hinkley**		0.09
	Overall change 1976-2011	+32%	
	1976-1989	NT	
	1990-2011	+32%	
			
198	**Snake River – Pine City**		0.12
	Overall change 1991-2010	NT	
			

Cedar and Des Moines River results

The Cedar River has among the highest nitrate concentrations of rivers in Minnesota. Nitrate concentrations in the Cedar River have been steadily increasing since 1967 (Table 11), with increases averaging 1% per year at Lansing (1980-2010) and 2% per year at Austin (1967-2009). No statistically significant trend was found for the West Fork Des Moines River near Petersburg (Table 12).

Table 11. Trends in flow-adjusted nitrate concentrations at two sites along the Cedar River. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend. Site No. refers to site location on Figure 1 and Table 1.

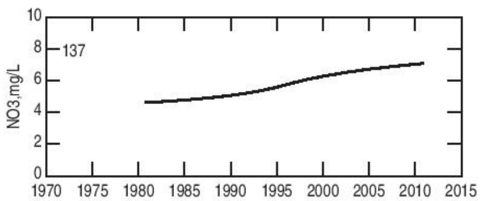
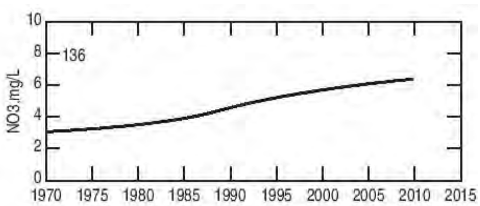
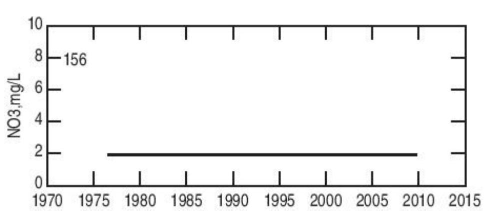
Site No.	Cedar River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
137	**Cedar River – Lansing**		7.1
	Overall change 1980-2010	+53%	
			
136	**Cedar River - Austin**		6.4
	Overall change 1967-2009	+113%	
			

Table 12. Trends in flow-adjusted nitrate concentrations in the West Fork Des Moines River. “NT” (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

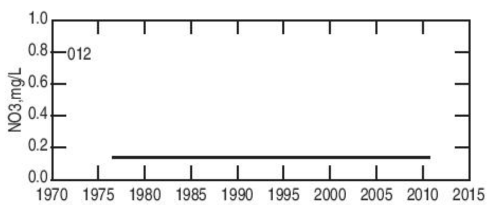
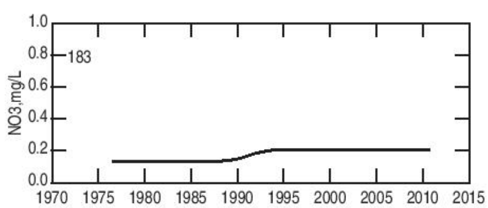
Site No.	Des Moines River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
156	**West Fork Des Moines River – Petersburg**		1.9
	Overall change 1976-2009	NT	
			

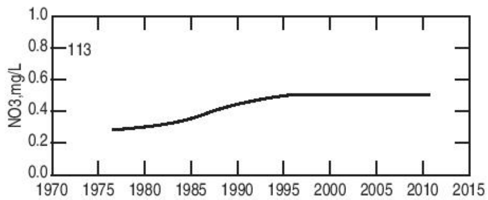
Red River of the North results

Red River of the North

Three sites on the Red River of the North were analyzed for trends in flow-adjusted nitrate concentrations. All three sites had relatively low nitrate concentrations, although the concentrations were higher at the downstream site in Perley. No trends were detected at the upper-most location at Brushvale. At Moorhead, and just downstream from Moorhead at Perley, concentrations increased prior to 1993-95, but had no significant trends after 1993 and 1995, respectively (Table 13).

Table 13. Trends in flow-adjusted nitrate concentrations at three locations along the Red River of the North. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

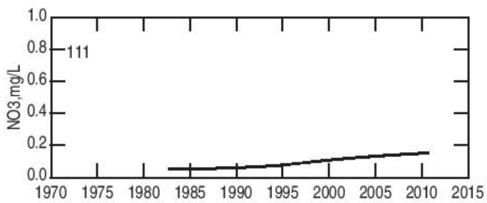
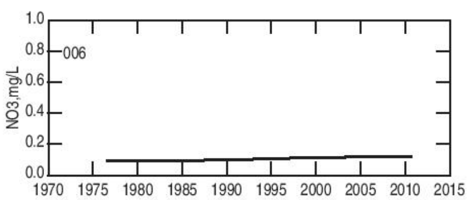
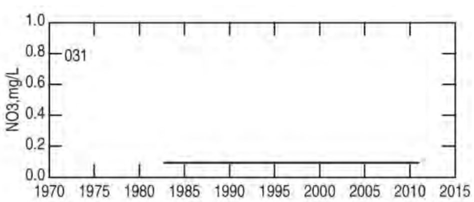
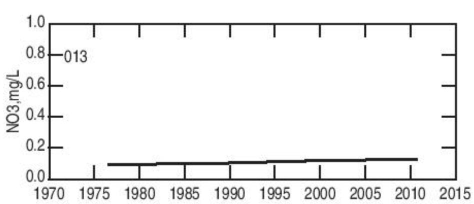
Site No.	Red River of the North Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
012	**Red River - Brushvale**		0.14
	Overall change 1976-2010	NT	
			
Site No.	**Red River of the North Site Location / Trend Analysis Periods**	**% Change in Nitrate Concentration**	**Ending Concentration, mg/l**
183	**Red River - Moorhead**		0.21
	Overall change 1976-2010	+53%	
	1976-1987	NT	
	1988-1993	+53%	
	1994-2010	NT	
			

113	**Red River - Perley**		0.51
	Overall change 1976-2010	+78%	
	1976-1995	+78%	
	1996-2010	NT	
			

Tributaries of the Red River of the North

Trends were assessed for two tributaries of the Red River of the North, the Ottertail River and the Red Lake River, each with two monitoring locations. Similar to the Red River of the North at Brushvale, nitrate concentrations were very low, mostly between 0.1 and 0.15 mg/l. At these low concentrations, the Ottertail River showed a steady increasing trend since 1982. The percentage increase was greater in Fergus Falls than at the downstream site at Breckenridge (Table 14). The Red Lake River at East Grand Forks had a trend very similar to that of the Ottertail River in Breckenridge, both with gradually increasing nitrate concentrations by 35% over the entire time of analysis. Farther upstream at Fisher, no trends were detected.

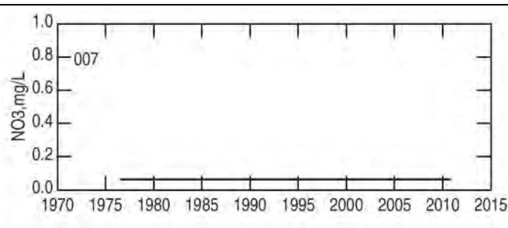
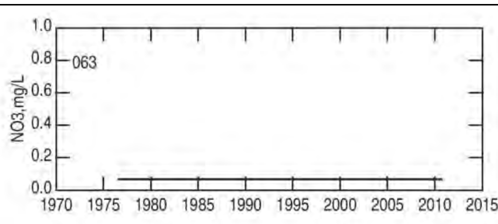
Table 14. Trends in flow-adjusted nitrate concentrations in four tributaries of the Red River of the North. A positive change in nitrate concentration represents a statistically significant ($p<0.1$) upward trend. “NT” (no trend) indicates that the trend was not statistically significant ($p<0.1$). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Tributaries – Red River of the North Basin Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
111	**Ottertail River – Fergus Falls**		0.15
	Overall change 1982-2010	+207%	
			
006	**Ottertail River – Breckenridge**		0.12
	Overall change 1976-2010	+35%	
			
031	**Red Lake River - Fisher**		0.09
	Overall change 1982-2010	NT	
			
013	**Red Lake River – East Grand Forks**		0.13
	Overall change 1976-2010	+35%	
			

Rainy and Western Lake Superior basins

The Rainy River had no substantial increases or decreases in flow-adjusted nitrate concentrations over the analysis period, with a concentration change at International Falls that rounded to 0%, and no significant trend at Baudette (Table 15). Concentrations have remained very low at both sites on the Rainy River since 1976.

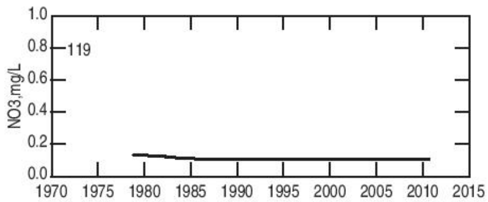
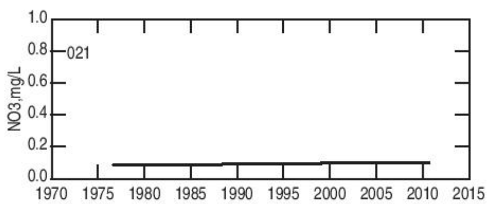
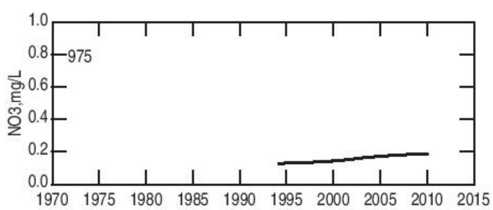
Table 15. Trends in flow-adjusted nitrate concentrations at two locations on the Rainy River. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	Rainy River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
007	**Rainy River – International Falls**		0.06
	Overall change 1976-2010	*0%	
			
063	**Rainy River - Baudette**		0.06
	Overall change 1976-2010	NT	
			

* The trend was statistically significant, but was so small that it rounded to zero.

The St. Louis River (within the Western Lake Superior Basin), also with very low nitrate concentrations, had fairly stable trends at Forbes and Fond Du Lac, with a slight decrease in concentrations at Forbes and a slight increase at Fond Du Lac. In Duluth, nitrate concentrations in the St. Louis River increased by 47% since 1994 (Table 16).

Table 16. Trends in flow-adjusted nitrate concentrations at three locations on the St. Louis River. A positive change in nitrate concentration represents a statistically significant (p<0.1) upward trend, and a negative change represents a statistically significant downward trend. "NT" (no trend) indicates that the trend was not statistically significant (p<0.1). Site No. refers to site location on Figure 1 and Table 1.

Site No.	St. Louis River Site Location / Trend Analysis Periods	% Change in Nitrate Concentration	Ending Concentration, mg/l
119	**St. Louis River - Forbes**		0.11
	Overall change 1978-2010	-20%	
	1978-1986	-20%	
	1987-2010	NT	
			
021	**St. Louis River – Fond Du Lac**		0.10
	Overall change 1976-2010	+16%	
			
113	**St. Louis River - Duluth**		0.19
	Overall change 1994-2010	+47%	
			

Discussion

Comparison with previous studies

Results of nitrate, TN, and ammonium concentrations and load trends from previous Minnesota studies are described in Chapter C2. In this discussion, we will compare only the nitrate concentration trends from previous studies to nitrate concentration trends reported in this chapter. None of the results are directly comparable because of differences in one or more of the following: trend analysis timeframe; location on the river; and/or statistical analysis/streamflow adjustment methods. Yet, several sites from past studies were close enough in location and timeframe to allow some comparison. In general, the results in this study agreed reasonably well with previous studies where comparisons were possible, except that the magnitude of change was consistently higher in this study as compared to previous studies. Comparisons in specific rivers are described below.

Mississippi River

The 76% increase in nitrate concentrations observed by Sprague et al. (2011) in the Mississippi River between 1980 and 2008 at Clinton, Iowa, are reasonably similar to the 107 and 109% increases in the Mississippi River found in this study at the two most downstream Mississippi River sites at LaCrosse, Wisconsin, and Minneiska, Minnesota (1976 to 2008).

Lafrancois et al. (2013) found increases in the Mississippi River from Anoka to Hastings ranging from 47 to 59% between 1976 and 2006, with one of six sites having no statistically significant trend. Increases were also found in our study, yet the increases were found to be larger during the extended timeframe assessed in this study (1976 to 2010-11). We found increases of 87% to 206% at six Mississippi River sites between Anoka and Prescott.

Minnesota River

Previous trend studies for the lower part of the Minnesota River Basin showed that nitrate concentrations either had no significant trend or an overall decreasing trend, with a few exceptions. This study showed several periods of decreasing trends in the Minnesota River, yet we also found other periods of increases. In the Minnesota River at Jordan, all studies showed little overall change in nitrate concentrations in the Minnesota River from the late 1970s to the early 2000s (Table 17), although this study indicated a slight increase from 1979 to 2004 and the other studies showed either no trend or a slight decrease over slightly different timeframes. The magnitude of change shown from all studies in the Minnesota River is small considering the long period of record.

Table 17. Results of different trend studies of nitrate concentration in the Minnesota River at Jordan, along with the findings in this study. A positive change in nitrate concentration represents an upward trend, and a negative change represents a downward trend.

Timeframe	% Change in Nitrate Concentration	Author
1979-2004	+19%	This Study
1976-2006	No significant trend	Lafrancois et al. (2013)
1976-2002	-20%	Kloiber (2004)
1979-2003	-10%	Johnson (2006)

St. Croix River

Kloiber (2004) found a 17% increase in nitrate concentrations in the St. Croix River at Stillwater between 1976 and 2002. This study found an increase at this same site between 1976 and 2004, but the magnitude of the increase was higher in this study (49%).

Red River of the North

At the border between Minnesota and Manitoba, Canada, Vechia (2005) found that nitrate concentrations increased in the Red River of the North by 27% from 1982 to 1992, followed by a no-trend period from 1993 to 2001. Lorenz et al. (2009) found no trend at Grand Forks from 1999 to 2008.

The farthest downstream site on the Red River of the North evaluated for this study was at Perley, for which results were generally similar to what Vechia and Lorenz found farther downstream, with an increasing trend through 1995, and no significant trend after that (1996 to 2010).

Lag time with groundwater flow

The velocity of groundwater flow is commonly measured in terms of feet per year. It can take many years to many decades before nitrate leaching through the soil near its source will ultimately move with groundwater and discharge into a river or stream. As described in appendix B5-1, much of the nitrate can be lost during this groundwater transport process due to denitrification prior to entering surface waters.

The lag time between nitrate leaching through the soil and into groundwater and its subsequent movement to streams depends on many factors, such as soils, geology, topography, and proximity to streams. Groundwater near a stream can enter surface waters within a matter of days or weeks. Water that is farther from streams can travel to streams in timeframes ranging from days to decades to centuries, depending on the hydrogeology (see http://www.dnr.state.mn.us/waters/groundwater_section/mapping/sensitivity.html). Streams fed by shallow surficial aquifers contain a mix of waters, some of which entered the ground many years earlier and some of which recently entered the groundwater (Puckett et al., 2011).

This groundwater lag time effect can greatly affect observed trends. The nitrate concentrations observed in the river integrate the consequences of land use and management in recent years with that of land use and management occurring years to decades earlier. The complete effects of modern era commercial fertilizer use, crop genetics, and management may not yet be realized in nitrate concentrations in the river.

For example, nearly one-half of the estimated cropland N sources in the Upper Mississippi River Basin come from groundwater flow; with the rest from tile lines and surface runoff (see Chapters D1 and D4). Because of the long lag time between nitrate entering groundwater and the eventual discharge of the affected groundwater into surface waters in this basin, nitrate pollution that occurred many years to many decades ago may be a large part of the nitrate just now entering streams and rivers. Therefore, the increasing nitrate concentrations in the Mississippi River do not necessarily mean that we are currently using practices that are causing higher nitrate loads in the river than a decade or two ago.

The lag-time effect of nitrate moving from groundwater into surface waters is also expected to be a dominant process affecting trends in other basins such as the St. Croix, Red River of the North, and Lower Mississippi Basins, which each have more than one-half of the estimated cropland nitrate moving into surface waters through groundwater pathways (see Chapter D1).

In basins with a higher fraction of the nitrate moving through tile drainage, the groundwater lag time will have less of an effect on observed concentration trends in rivers. The Minnesota River Basin has about 18% of its estimated cropland N transported via groundwater (Chapters D1 and D4), and is dominated instead by the quicker-responding tile drainage flow pathway (75% of the estimated cropland N). Nitrate concentrations in the lower part of the Minnesota River were increasing until the 2001-2005 timeframe, at which time the trends reversed to show declining concentrations through 2009-11 (Table 7). The Des Moines River Basin and Cedar River Basin also have a major nitrate pathway through tile lines (55-70% of estimated cropland N). Nitrate concentration trends in the Cedar River were continuously upward (Table 11). Estimates of source pathways in Chapter D1 indicate that more N enters the Cedar River from groundwater (39%) as compared to the Minnesota River (18%). No significant trends were found in the Des Moines River (Table 12), where groundwater contributes an estimated 23% of the N.

Changes in land management and precipitation

Many factors potentially affect nitrate concentration trends, including changes in crops/vegetation; fertilizer management and N use efficiency; human population and wastewater treatment processes; livestock/poultry populations and manure management practices; climate/precipitation; soil mineralization; and flow pathways—tile drainage, groundwater, and runoff.

It was beyond the scope of this study to investigate the relation between trends in river nitrate concentrations and changes in land use and hydrologic factors expected to affect nitrate concentrations. Changes in certain variables that have the potential to affect river nitrate concentrations are summarized below. Future studies that more thoroughly explore possible reasons for changes in nitrate concentrations could be useful for understanding the most important factors affecting nitrate increases and decreases.

Fertilizer use

Minnesota N fertilizer sales have followed a similar pattern as national fertilizer sales (Figure 6). Fertilizer sales increased markedly between 1965 and 1980, followed by leveling off of sales and a gradual long-term overall increasing trend between 1980 and 2011. The average statewide N application rate per acre on corn cropland started leveling off in the early 1970s, with a gradual increasing rate from 1972 until the early 1980s (Figure 7). Fertilizer application rates per acre of corn cropland appear to have been relatively stable to slightly increasing from the late 1980s until about 2010, according to information provided by the Minnesota Department of Agriculture (MDA, 2013).

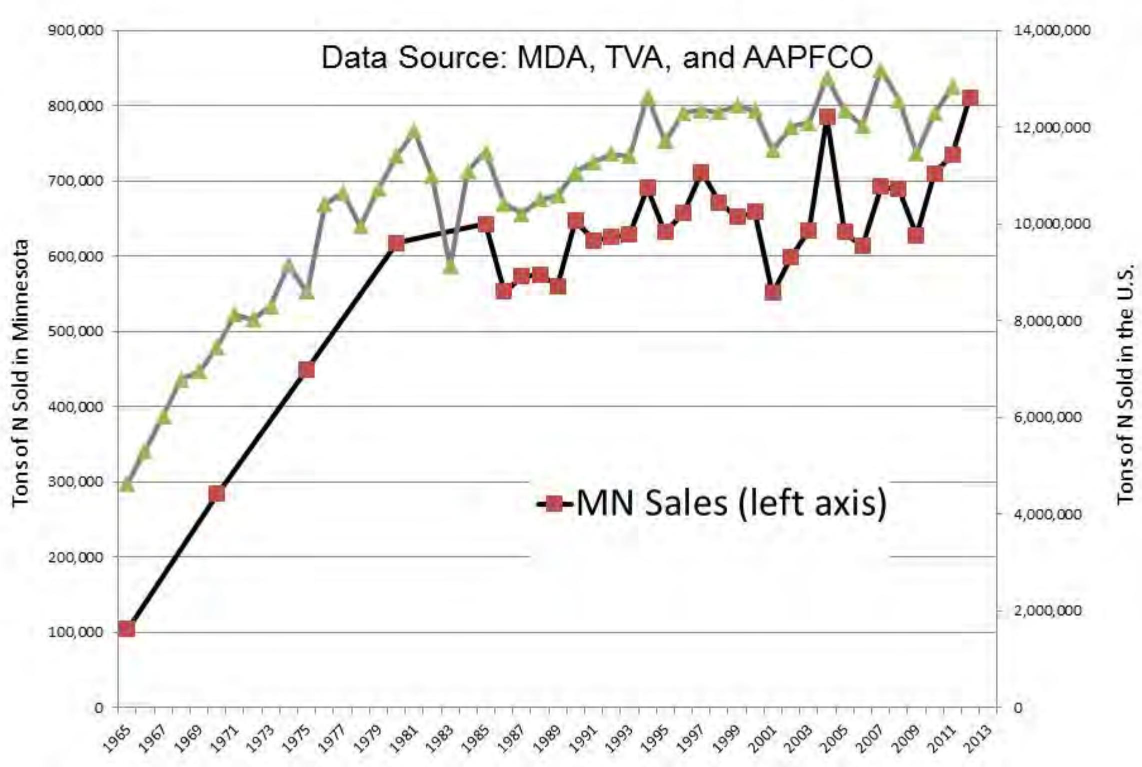


Figure 6. Commercial nitrogen (N) fertilizer sales from 1965 to 2011 in the United States (green) and in Minnesota (red). Graph from MDA (2013). Data sources are Minnesota Department of Agriculture (MDA), Tennessee Valley Authority and Association of American Plant Food Control Officials.

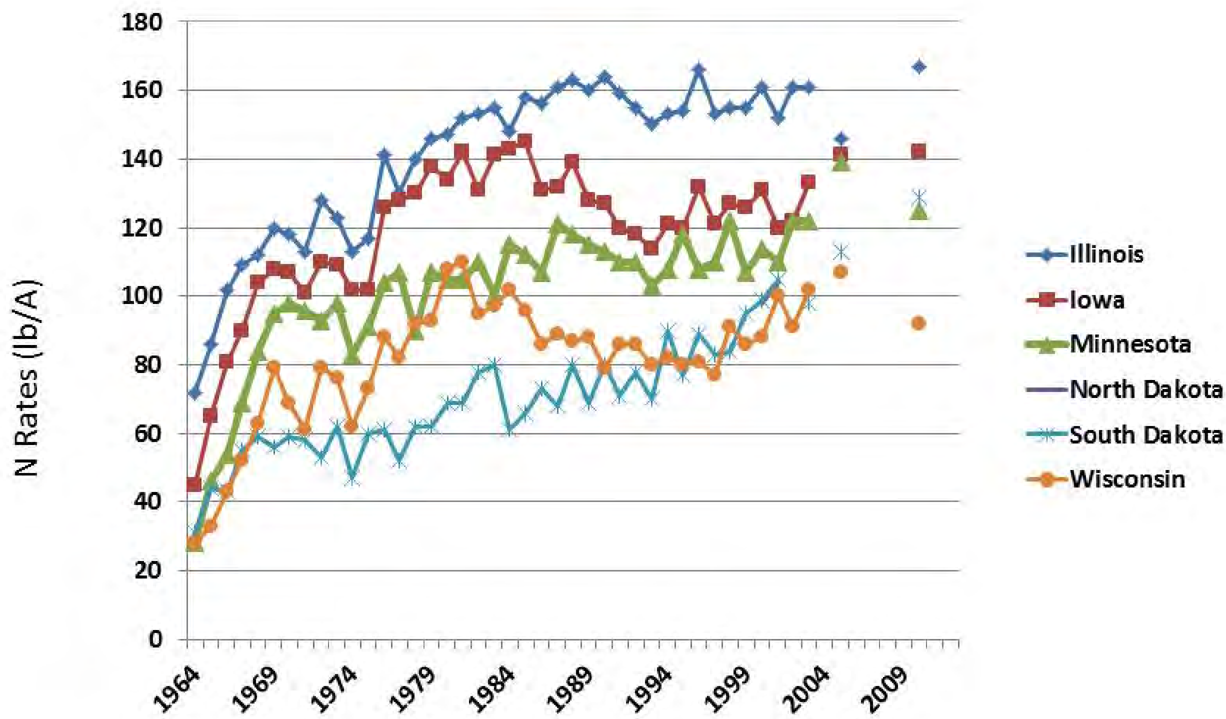


Figure 7. Midwest states' nitrogen (N) fertilizer application rates (in pounds per acre) for corn from 1964 to 2010. Graph from MDA (2013). Data sources: ERS/NASS (Economic Research Service and National Agricultural Statistics Service).

Crop nitrogen fertilizer use efficiency

An estimated 31% of statewide N outputs from agricultural lands go into the atmosphere, mostly through the three processes of senescence, denitrification in soil, and volatilization, and an estimated 6% of N outputs go into groundwater and surface waters (see Chapter D4). The remaining 63% of N from agricultural lands goes into crops and food products. As N fertilizer use becomes more efficient through plant genetics and improved management practices, more of the N goes into crops and potentially less is lost into the atmosphere and into waters. The N fertilizer use efficiency has been increasing over the past decades according to information assembled by the Minnesota Department of Agriculture. The bushels of corn produced per pound of N fertilizer input (crop N use efficiency) has increased from about 0.8 in 1992 to about 1.2 in 2011 (Figure 8; MDA, 2013). It is possible that more of the N is now used by the crop and less N may therefore be available in the soil for potential losses to the air and water for each bushel of corn produced. The potential benefits of this trend to water quality, however, may be offset somewhat as corn protein content decreases and as more corn is grown per acre. Additional study is needed of the water-quality effects from such changes.

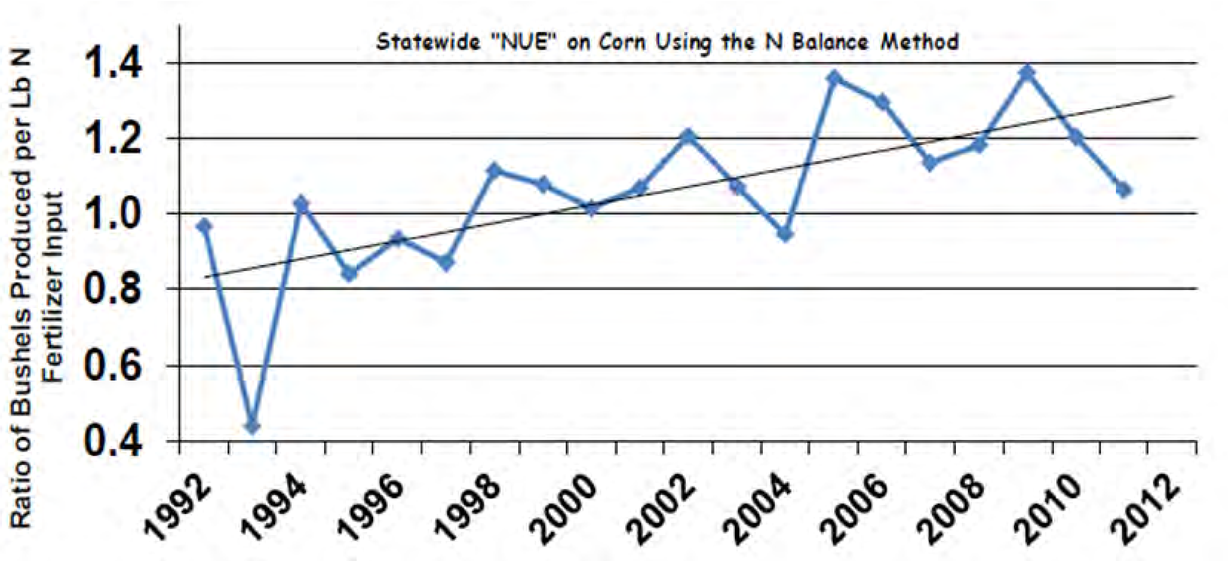


Figure 8. Bushels of corn produced per pound of N fertilizer applied to corn cropland, 1992 to 2011. Graph from MDA (2013).

Livestock/poultry manure

Based on U.S. Department of Agriculture National Agricultural Statistics Service (www.nass.usda.gov/data_and_statistics/index.asp) inventories between 1974 and 2007, Minnesota cattle and calf numbers have declined by 35% (most affected by dairy declines), while swine numbers have more than doubled and turkeys have more than tripled. The total number of animal units in the state, as animal units are defined in Minn. R. ch. 7020, has generally remained constant since 1974 (Figure 9). Decreasing cattle were offset by the increasing swine and turkey numbers.

When we multiply the animal numbers by typical manure N content for different livestock species, the estimated amount of manure N from livestock and poultry being applied onto cropland was not found to vary by more than 12% between 1974 and 2007, and estimated manure N amounts applied statewide in 2007 were only 1% more than applied in 1974. It is also possible that even though the amount of manure N being generated and applied to lands has not changed much, the amount of manure N entering waters may have changed (i.e. less manure N entering waters).

Manure management changed considerably throughout this period (1974 to 2007) as more liquid manure storage pits and basins were constructed, replacing solid manure handling systems (based on author's 16 years of experience working in the MPCA Feedlot program). Methods of application correspondingly changed, and injection of liquid manure below the ground surface became more popular. We expect that these changes may have resulted in more predictability in available N from manure for crops, and therefore improved manure management and less N losses to waters.

During 2000, Minnesota changed its feedlot regulations related to manure spreading (Minn. R. ch. 7020.2225). The effects of these regulations on N management have not been researched. It is possible that the new regulations resulted in improved N management and less N losses to waters. The rule changes affecting N management included requirements for nutrient management plan development, record-keeping of manure spreading, and laboratory testing of manure N content.

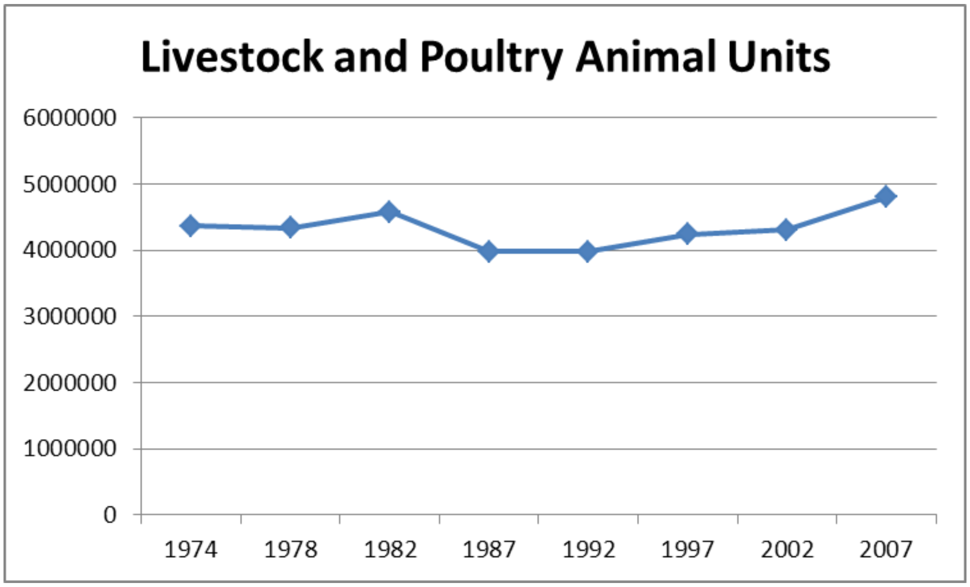


Figure 9. Trends of total animal units (AUs) in Minnesota based on USDA National Agricultural Statistics Service data (www.nass.usda.gov/) and the following conversion factors: dairy cow - 1.4 AUs; beef cow - 1 AU; other cattle and calves avg. - 0.7 AU; swine and hogs - 0.3 AU; turkeys - 0.018 AU; chickens - 0.003 AU.

Human population

The Minnesota population has been growing steadily from 4 million people in 1980 to 5.4 million in 2012 (United States Census Bureau – www.census.gov). The increased population would be expected to have a corresponding increase in human wastewater N discharges from municipalities and septic systems. Because of wastewater treatment system upgrades at approximately 110 municipal and industrial wastewater treatment facilities with ammonia limits in the 1980s and 1990s, the form of N released to waters changed from ammonia+ammonium to nitrate at these sites (Bruce Henningsgaard, MPCA, personal communication, 2013).

Cropping changes

Since the mid-1960s, row crop acreages have increased substantially in Minnesota (MDA, 2013). Corn acreage has increased by more than 30% (Figure 10) and soybean acreage has more than doubled (Figure 11). At the same time, alfalfa and clover, which contribute low levels of N to waters, have decreased by more than 40%.

Between 2006 and 2011, Minnesota's net loss of grasslands converted to corn/soybeans was 196,000 acres (Wright and Wimberly, 2013).

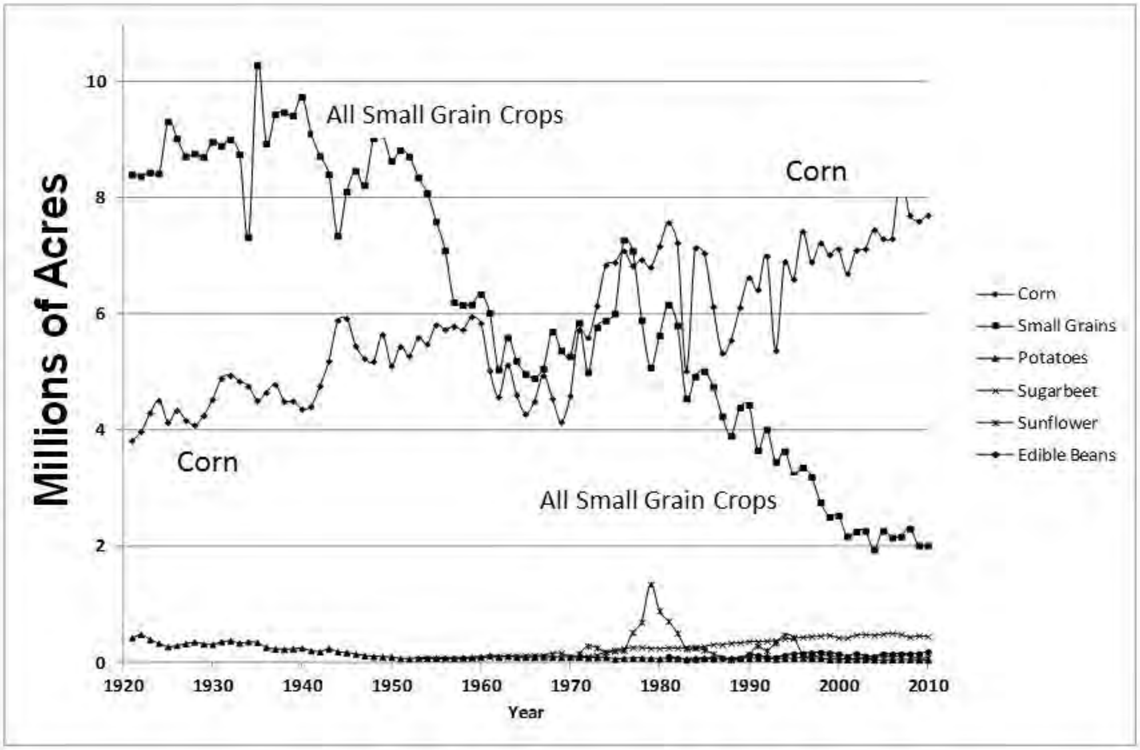


Figure 10. Trends in acreage planted to corn and small grain crops in Minnesota between 1920 and 2011. From MDA (2013).

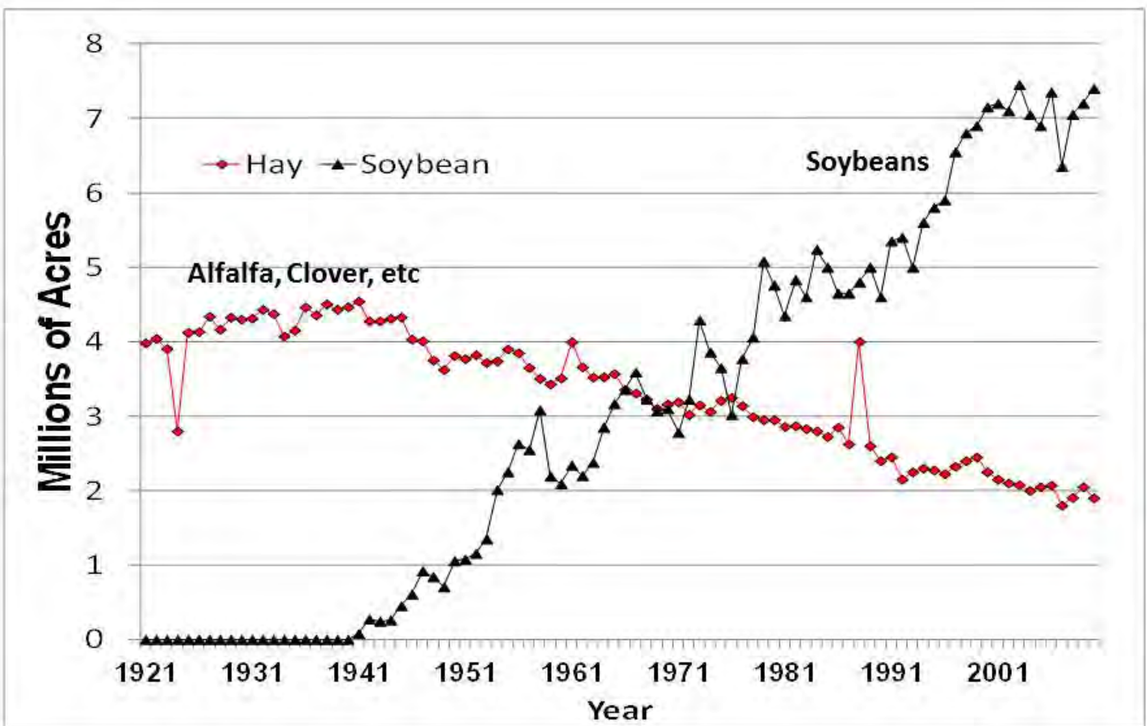


Figure 11. Trends in acreage planted to soybeans (black line) and other legumes (red line) in Minnesota between 1921 and 2011.

Tile drainage changes

Tile drains continue to be installed and replaced in Minnesota soils. The rate of increasing tile drainage is not well documented in the state and was not quantified for this study.

Precipitation changes

Between 1975 and 1995, the statewide annual average precipitation trends showed numerous wet and dry periods. Since 1995, statewide 7-year moving average precipitation has remained relatively high compared to historical levels, with a fairly stable trend compared to other times since 1890 (Figure 12).

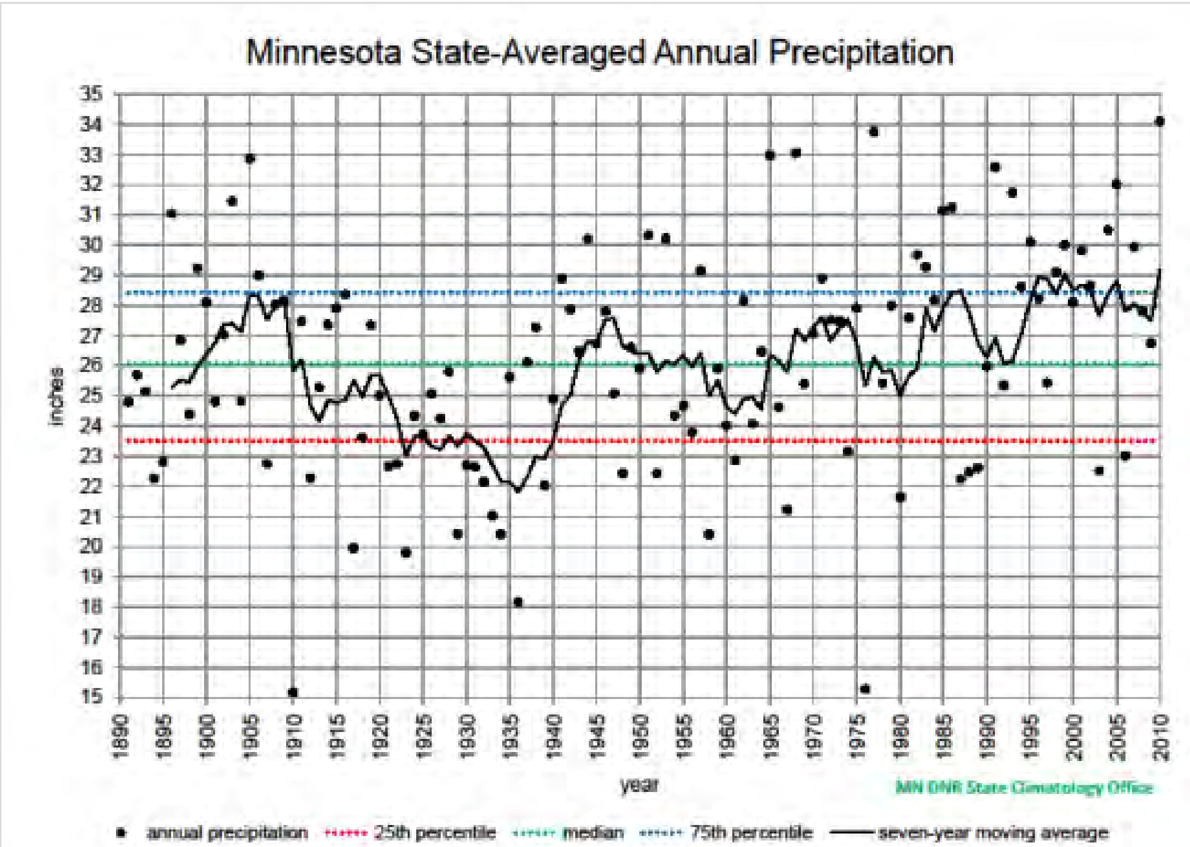


Figure 12. Long-term precipitation patterns in Minnesota since 1890. From MN DNR State Climatology Office (http://climate.umn.edu/pdf/minnesota_state_averaged_precipitation.pdf).

Figures 13 to 20 show spatial average annual precipitation amounts across several HUC8 watersheds in different regions of the state from 1980 to 2009, developed from precipitation data provided by the Minnesota Department of Natural Resources (Greg Spoden, written communication, 2011). Overall, the precipitation trends in this timeframe did not show major overall changes, although slight increases or slight decreases in annual precipitation are evident in some watersheds (Figures 13-19). A region of the state with a more consistent upward trend over this period is northwestern Minnesota in the Red River Basin (Figure 20). See Figure 4 for locations of watersheds.

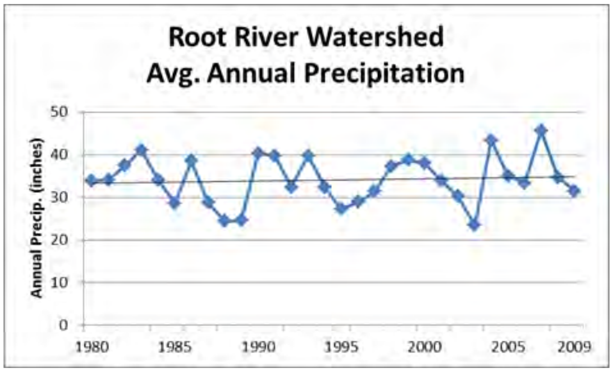


Figure 13. Spatial average annual precipitation amounts for the Root River Watershed from 1980 to 2009.

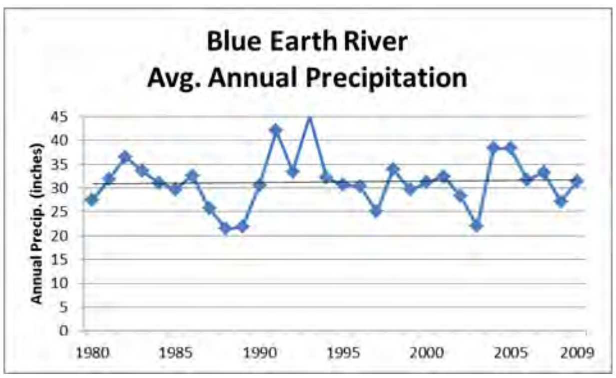


Figure 14. Spatial average annual precipitation amounts for the Blue Earth River Watershed from 1980 to 2009.

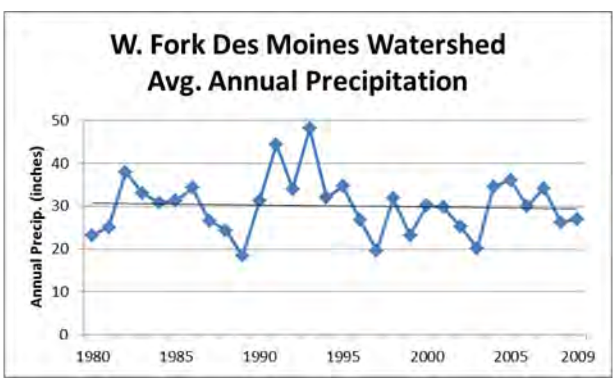


Figure 15. Spatial average annual precipitation amounts for the West Fork Des Moines River Watershed from 1980 to 2009.

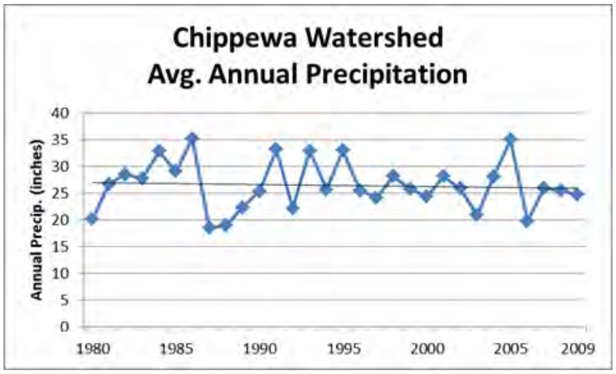


Figure 16. Spatial average annual precipitation amounts for the Chippewa Watershed from 1980 to 2009.

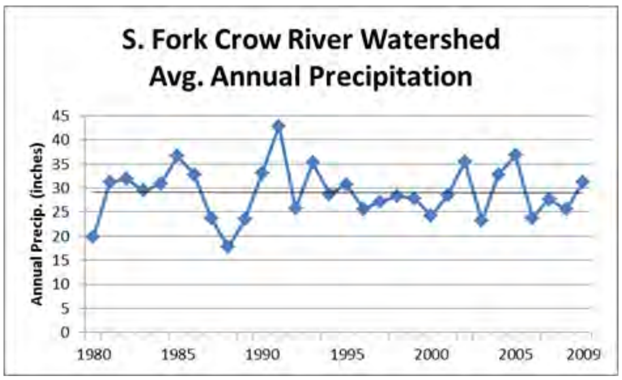


Figure 17. Spatial average annual precipitation amounts for the South Fork Crow River Watershed from 1980 to 2009.

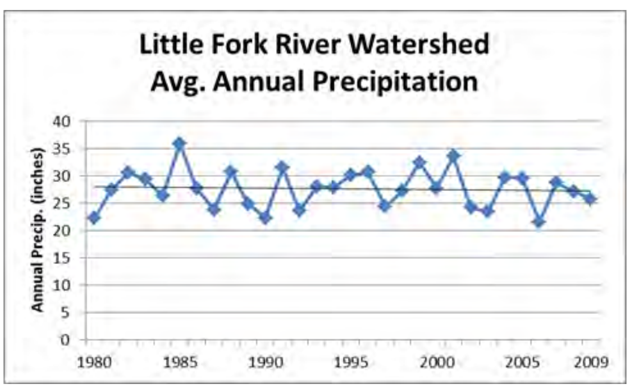


Figure 18. Spatial average annual precipitation amounts for the Little Fork River Watershed from 1980 to 2009.

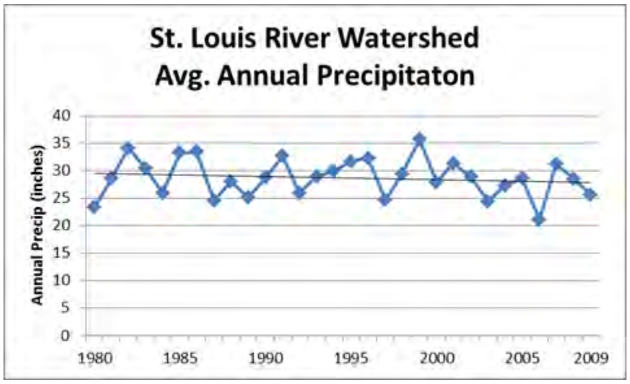


Figure 19. Spatial average annual precipitation amounts for St. Louis River Watershed from 1980 to 2009.

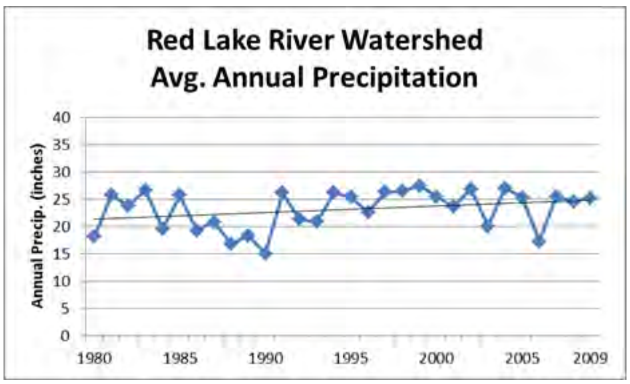


Figure 20. Spatial average annual precipitation amounts for the Red Lake River Watershed from 1980 to 2009.

Relation between streamflow and nitrate concentrations – a QWTREND analysis

The QWTREND model was used to evaluate the relation between streamflow and nitrate concentrations using four different time period assessments: (1) seasonal – 90 day periods, (2) annual, (3) 5-year, and (4) High-Frequency Variability (HFV) – short-term events. A positive streamflow anomaly coefficient indicates a direct relation between streamflow and nitrate concentrations, such that nitrate concentrations are statistically higher during high-flow periods. A negative coefficient indicates a negative relation between streamflow and nitrate concentrations. A higher magnitude coefficient represents a stronger relation, such that coefficients in the range of 0.4 to 0.8 represent a very strong relation between streamflow and nitrate concentrations.

Most of the rivers had a positive coefficient for the seasonal, annual, and HFV periods of time, indicating that the average nitrate concentrations over the 90-day, annual, and short-term event time periods are typically higher when streamflows are higher. One exception was the Rainy River, which had such low coefficients that essentially no relation was evident between streamflow and nitrate concentrations. In general, the coefficients were larger for the southern part of Minnesota than in the northern part, indicating a stronger relation between streamflow and nitrate concentrations in parts of the state where nitrate concentrations and effects of human activities on nitrate concentrations are higher.

The streamflow anomaly coefficients were larger for the 90-day and annual averages than for the 5-year average (Table 18), indicating that nitrate variation from season to season or year to year is more highly correlated to streamflow than is the 5-year average streamflow.

Analyses indicated that the Minnesota River Basin has a strong direct correlation between streamflow and nitrate concentrations for all types of time periods evaluated, but was highest for the seasonal averages. By comparison, the Upper Mississippi River Basin, which is affected more by groundwater base flow than by tile drainage, had lower coefficients and thus a weaker relation between streamflow and nitrate concentrations.

Some of the coefficients for the 5-year anomaly were negative, although the negative relations were weak at all sites (low coefficient magnitude), except for the Mississippi River between the Minnesota and the St. Croix Rivers. The negative long-term (5-year) coefficients may be at least partly attributable to the dilution of wastewater because the strongest negative signal for those coefficients was downstream from the Twin Cities.

Overall, the pattern of the coefficients indicates that surplus nitrate is flushed through the soil or off the soil by both rainfall/snowmelt events and by sustained wet periods, particularly in the agricultural areas of the state.

Table 18. Mean model coefficients for the streamflow anomalies by basin. Coefficients greater than 0.2 are highlighted in green.

Seasonal (90 day average streamflow)	Annual	5-Year	HFV (event flushing – seasonal component)
Upper Mississippi River Basin			
0.197	0.197	-0.121	0.082
Mississippi River between Minnesota and St. Croix Rivers			
0.569	0.768	-0.205	0.250
Lower Mississippi River			
0.988	0.768	-0.056	0.100
Tributaries to the Lower Mississippi River			
0.226	0.178	0.046	0.075
Minnesota River Basin			
0.703	0.649	0.453	0.269
St. Croix River Basin			
0.041	0.014	-0.008	0.002
Cedar and Des Moines River Basins			
0.521	0.521	0.240	0.233
Red River of the North Basin			
0.133	0.026	0.011	0.178
Rainy River Basin			
-0.0001	0.018	-0.075	-0.003
St. Louis River			
0.120	0.287	0.011	0.001

Summary of nitrate trends results

Flow-adjusted nitrate concentrations in the Mississippi River increased between 1976 and 2010 at most sites on the river, with overall increases in nitrate concentrations ranging from 87% to 268% everywhere except the most upstream location at Blackberry (0% change). Three of the 10 sites with increases showed a leveling off of the increase or no-trend starting in the early to late-1990s (Camp Ripley, Grey Cloud, and Hastings). The other 7 sites had a continuous increase in concentrations over the analysis period. During recent years, the annual increases everywhere downstream from Clearwater have ranged from 1% to 4% (except that no significant trend was detected at Grey Cloud and Hastings). The two most upstream sites at Blackberry and Camp Ripley have recently shown a downward trend and no trend, respectfully. Results from the small number of tributaries to the Mississippi River for which trends could be analyzed showed trends that did not always match the Mississippi River trends. For example, several tributaries, including the Rum, Straight, Cannon, and Zumbro Rivers, had downward trends in recent years.

Trends in flow-adjusted nitrate concentrations in the Minnesota River were somewhat different at different points along the river. The two most upstream sites at Courtland and St. Peter had no trend after 1987. The St. Peter and Henderson sites had an increase from 1976 to 1981, followed by a decrease between 1982 and 1986. After 1986, the Henderson site had a pattern similar to patterns at the Jordan and Fort Snelling sites. All three downstream sites (Henderson, Jordan, and Fort Snelling) showed a steady gradual increase in nitrate concentrations through 2004, followed by a decrease between 2005 and 2010. The overall long-term net changes at the three downstream sites were +50% (Henderson), -26% (Jordan), and -6% (Fort Snelling). During recent years, all sites on the Minnesota River and most tributaries to the Minnesota River had a downward trend or no trend. The only exception is the Watonwan River, which had a slight increase in concentrations of about 1% per year.

In a couple of the smaller upstream stretches of main-stem rivers originating in Minnesota, the Cedar River showed a steady increase in nitrate concentrations of 113% over a 43-year period, whereas the West Fork of the Des Moines River showed no trend.

In northern Minnesota, the major rivers showed either no trend or a slight upward trend. All of these rivers had very low nitrate concentrations throughout the period of analysis. The Red River of the North showed significant increases in nitrate concentrations before 1995, but no trends since about that time. The St. Louis River at Duluth had the most change with a 47% increase between 1994 and 2010.

Overall, the findings showed generally similar trend patterns as previous trend studies conducted at the same or nearby locations, although there were some differences. The magnitude of change was typically larger in this study as compared to previous studies. Additionally, the slight increase in nitrate concentrations at the Minnesota River Jordan site from 1976 to 2003 was different from other studies, which showed no significant trend or a downward trend.

The reasons for the nitrate concentration changes were not determined. However, we noted several concurrent statewide land-use trends during the period of analysis. Acres planted to corn and soybeans increased, while small grain and alfalfa/clover acreages decreased. Fertilizer application increased, mostly prior to 1980, and has increased at a much slower rate since 1980. Manure N generation was essentially the same in 1974 and 2007, and overall corn N use efficiency has increased steadily since 1992, resulting in more corn grown for each pound of fertilizer used. Human population has increased from 4 to 5.4 million people. No strong trends in annual precipitation were evident during recent decades, except in northwestern Minnesota where annual precipitation has been increasing.

Future studies

Studies that might add to the understanding of nitrate trends include:

- Further explore the causes of nitrate concentration trends, particularly the decreases observed in downstream parts of the Minnesota River after 2005, and several periods of increases in other rivers between 1990 and 1995.
- As more TN and nitrate load results become available, analyze trends in loads.
- Assess typical lag times between adoption of best management practices and response of nitrate concentrations in rivers for which groundwater is the dominant pathway for nitrate to rivers.
- Re-evaluate trends periodically to see if recent short-term trends continue, such as the downward trends in the Minnesota River Basin.
- Use alternative statistical trend methods to compare against QWTREND methods used in this study.
- Assess nitrate load changes over time where monitoring is sufficient and land-use changes have been made.

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