Executive Summary
Nitrogen in Minnesota Surface Waters

Conditions, trends, sources, and reductions

Minnesota Pollution Control Agency

June 2013

Prepared by the Minnesota Pollution Control Agency, in collaboration with the University of Minnesota and U.S. Geological Survey

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Executive Summary

Purpose

This study of nitrogen (N) in surface waters was conducted to better understand the N conditions in Minnesota's surface waters, along with the sources, pathways, trends and potential ways to reduce N in waters. Nitrogen is an essential component of all living things and is one of the most widely distributed elements in nature. Nitrate (NO_3), the dominant form of N in waters with high N, is commonly found in ground and surface waters throughout the country. Human activities can greatly increase nitrate, which is typically found at low levels in undisturbed landscapes.

Concern about N in Minnesota's surface waters has grown in recent decades due to: 1) increasing studies showing toxic effects of nitrate on aquatic life, 2) increasing N concentrations and loads in the Mississippi River combined with nitrogen's role in causing a large oxygen-depleted zone in the Gulf of Mexico, and 3) the discovery that some Minnesota streams exceed the 10 milligrams per liter (mg/l) standard established to protect potential drinking water sources.

Minnesota recently initiated two state-level efforts related to N in surface waters. The Minnesota Pollution Control Agency (MPCA) is developing water quality standards to protect aquatic life from the toxic effects of high nitrate concentrations. The standards development effort, which is required under a 2010 Legislative directive, draws upon recent scientific studies that identify the concentrations of nitrate harmful to fish and other aquatic life.

Also in development is a state-level Nutrient Reduction Strategy, as called for in the 2008 Gulf of Mexico Hypoxia Action Plan. Minnesota contributes the sixth highest N load to the Gulf and is one of 12 member states serving on the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. The cumulative N and phosphorus (P) contributions from several states are largely the cause of a hypoxic (low oxygen) zone in the Gulf of Mexico. This hypoxic zone affects commercial and recreational fishing and the overall health of the Gulf, since fish and other aquatic life cannot survive with low oxygen levels. Minnesota is developing a strategy which will identify how further progress can be made to reduce N and P entering both in-state and downstream waters.

The scientific foundation of information documented in this report will be useful as the MPCA and other state and federal organizations further their nitrogen-related work, and also as local government considers how high N levels might be reduced in their watersheds.

The Minnesota Department of Agriculture is completing a separate but concurrent effort to revise the state's Nitrogen Fertilizer Management Plan, as required under Minnesota's Ground Water Protection Act. The plan addresses groundwater protection from nitrate. Yet because groundwater baseflow is an important contributor to surface water nitrate, certain groundwater protection efforts will also benefit surface waters.

Approach

The general approach for conducting this study was to:

1) **Collaborate with other organizations.** This study was conducted and written by 15 authors and co-authors. The University of Minnesota led the assessment of agricultural and nonpoint sources of N.

The U.S. Geological Survey assisted with nitrate trends evaluations and certain modeling and mapping efforts. Assistance and review was provided by several other organizations including Metropolitan Council, Minnesota Department of Agriculture, Board of Water and Soil Resources, and others.

2) **Build from existing information, tools, and data**. The study incorporated:
    - Recent water N concentration results from more than 50,000 water samples collected at more than 700 stream sites in Minnesota;
    - Water N loads calculated from monitoring results at more than 75 Minnesota watersheds;
    - Monitoring results from approximately 1976 to 2010 at 50 river sampling sites in Minnesota;
    - Findings from more than 300 published studies;
    - Findings from six previously developed computer models and two newly developed models; and
    - More than 40 existing Geographic Information System (GIS) spatial data layers.
3) **Include both total nitrogen and nitrate.** The study assesses total nitrogen (TN) for understanding downstream N loads to the Gulf of Mexico and Lake Winnipeg, and also assesses the nitrate form of N (concentrations, loads, trends) due to its impact on in-state aquatic life and drinking water.
4) **Develop results for large scales**. Results were determined for large-scale areas, such as statewide, major basins, and 8-digit Hydrologic Unit Code (HUC8) watershed outlets. Minnesota has 81 HUC8 watersheds, each averaging over 1000 square miles. Results should not be applied to the small watershed scale.
5) **Verify results.** The study results were verified with alternative methods, data, and studies, so that the conclusions are supported by more than one approach.

Nitrogen conditions in surface waters

Nitrogen conditions in surface waters are usually characterized in four different ways: 1) concentration, 2) load, 3) yield, and 4) flow weighted mean concentration.

- *Concentrations* are determined by taking a sample of water and having a laboratory determine how much N mass is in a given volume of that water sample, typically reported as mg/l. Load is the amount of N passing a point on a river during a period of time, often measured as pounds of N per year.

- *Loads* are calculated by multiplying N concentrations by the amount of water flowing down the river. Nitrogen loads are influenced by watershed size, as well as land use, land management, hydrology, precipitation, and other factors.

- *Yield* is the amount (mass) of N per unit area coming out of a watershed during a given time period (i.e., pounds per acre per year). It is calculated by dividing the load by the watershed size, which then allows for comparisons of watersheds with different sizes.

- *Flow weighted mean concentration (FWMC)* is the weighted-average concentration over a period of time, giving the higher flow periods more weight and the lower flow periods less weight. The FWMC is calculated by dividing the total load for a given time period by the total flow volume during that same period, and is typically expressed as mg/l.

Nitrogen concentrations

Maximum nitrite+nitrate-N (nitrate) levels in Minnesota rivers and streams (years 2000-2010) exceeded 5 mg/l at 297 of 728 (41%) monitored sites across Minnesota, and exceeded 10 mg/l in 197 (27%) of these sites. A marked contrast exists between nitrate concentrations in the southern and northern parts of the state. In most southern Minnesota rivers and streams, nitrate concentrations at least occasionally exceed 5 mg/l (Figure 1). Most northeastern and northwestern Minnesota streams have nitrate concentrations which usually remain less than 1 and 3 mg/l, respectively.

Nitrate concentrations in southern Minnesota streams tend to fluctuate seasonally. However, seasonal variability is much less in several southeastern Minnesota streams, where groundwater baseflow provides a continuous supply of high nitrate water to streams throughout the year.

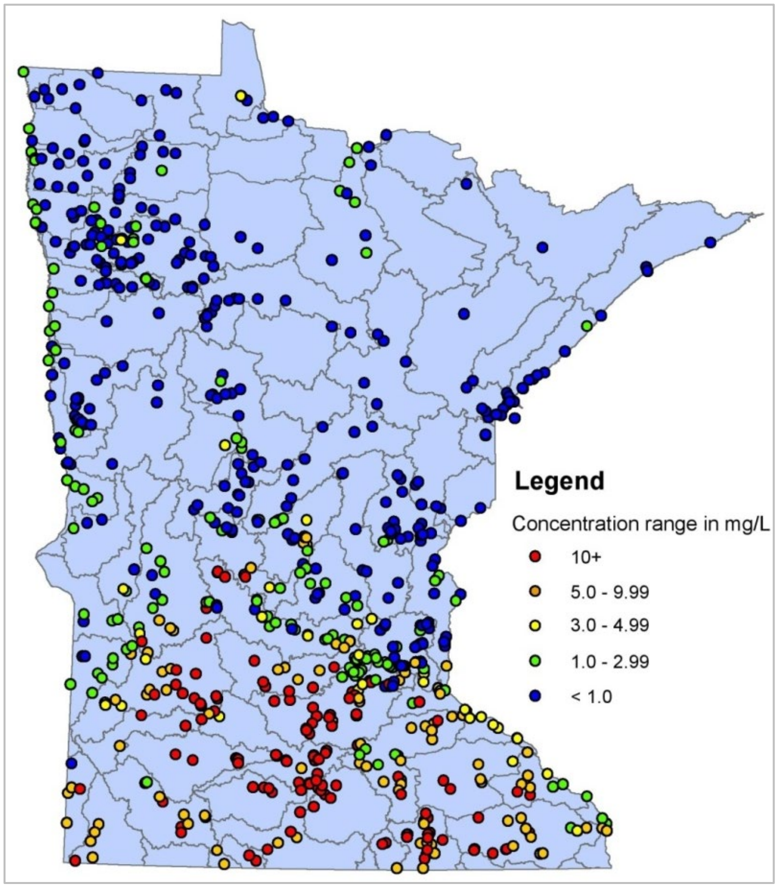


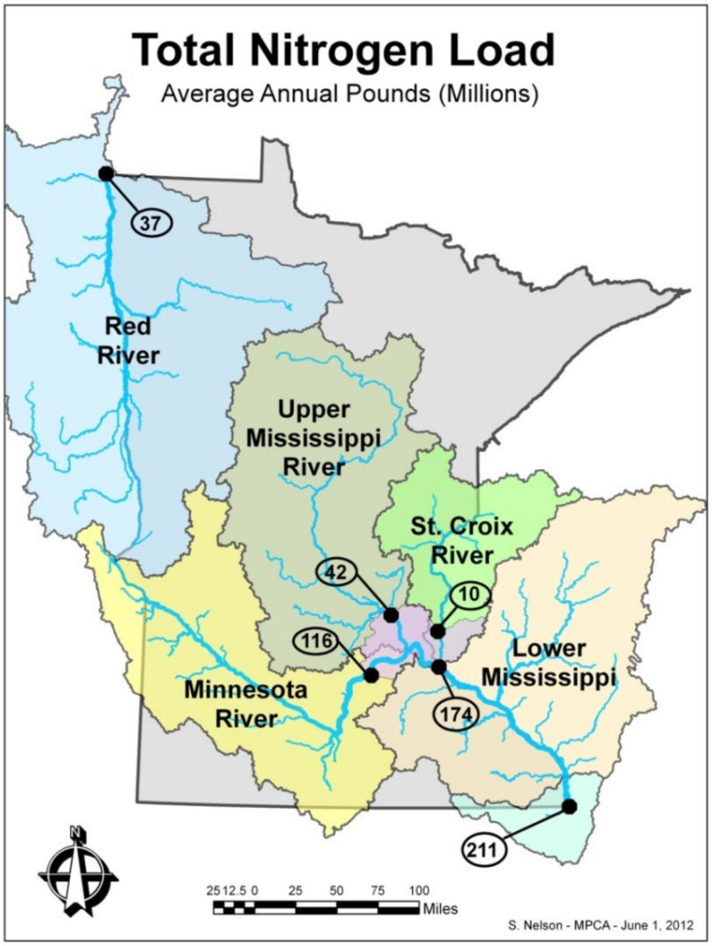
Figure 1. Nitrate concentrations at 728 river and stream sampling sites. Each colored circle shows the 90th percentile concentration from all samples taken at the site between 2000 and 2010.

Total nitrogen concentrations exhibit a similar spatial pattern across the state as nitrate, but are typically about 0.5 to 3 mg/l higher than nitrate-N, since TN also includes organic N and ammonia+ammonium (ammonium). Ammonium concentrations are less than 1 mg/l at 99% of river and stream sites in the state, and median concentrations are mostly less than 0.1 mg/l.

Mainstem river loads

Monitoring-based annual TN loads show that most of the state's TN load leaves Minnesota in the Mississippi River (Figure 2). On average, 211 million pounds of TN leaves Minnesota each year in the Mississippi River at the Minnesota-Iowa border, with just over three-fourths of this load originating in Minnesota watersheds, and the rest coming from Wisconsin, Iowa, and South Dakota. This compares to about 37 million pounds leaving the Red River at the Minnesota-Manitoba border, with about half from Minnesota and half from the Dakotas.

The highest TN-loading tributary to the Mississippi River is the Minnesota River, which adds about twice as much TN as the combined loads from the Upper Mississippi River (at Anoka) and St. Croix River (at Stillwater). The higher TN load in the Minnesota River is mostly due to much higher average TN concentrations in that river (8.2 mg/l flow-weighted mean concentration) as compared to the Upper Mississippi (2.2 mg/l) and the St. Croix River (1.0 mg/l).



South of the Twin Cities, tributaries from Wisconsin and Minnesota contribute additional N to the Mississippi River. Only small fractions of TN are lost in the Mississippi River, except where the water is backed-up for long periods in quiescent waters, allowing nitrate to be converted to N gas through natural processes or to be used by algae. In the river stretch between the Twin Cities and Iowa, some N is lost when river flow slows in Lake Pepin and in river pools behind locks and dams. Monitoring-based loads show that an average 9% TN loss occurs in Lake Pepin. An additional 3 to 13% of the river TN is estimated to be lost in the 168 mile Mississippi River stretch between the Twin Cities and Iowa. The net effect of the TN additions and losses in the Lower Mississippi Basin is an average 37 million pound annual TN load increase between the Twin Cities and Iowa.

Figure 2. Long term (15-20 year) average annual TN loads at key points along mainstem rivers.

Year-to-year variability in TN loads and river flow can be very high. In the Minnesota River Basin, TN loads during low flow years are sometimes as low as 25% of the loads occurring during high flow years. Major river TN loads typically reach monthly maximums in April and May. About two-thirds of the annual TN load in the Mississippi River at the Iowa border occurs during the months March through July, when both river flow and TN concentrations are typically highest.

Comparing watersheds

Watershed loads, yields and FWMCs were estimated for HUC8 level watersheds throughout the state so that different parts of the state could be compared and geographic priorities established. The two methods used to compare watersheds were: 1) monitoring results from the 2007 to 2009 period, and 2) SPARROW modeling that integrated long-term water monitoring data with landscape information and in-stream losses to estimate long-term average loads.

The monitoring results from 2007-2009 and SPARROW modeling results show similar parts of the state with high and low river N loads (Figures 3 and 4). The highest N yields occur in south central Minnesota, where TN FWMCs typically exceed 10 mg/l. The second highest TN yields are found in southeastern and southwestern Minnesota watersheds, which typically have TN FWMCs in the 5 to 9 mg/l range.

The highest three TN-yielding HUC8 watersheds include the Cedar River, Blue Earth River, and Le Sueur River watersheds, each yielding over 20 pounds/acre/year, on average. The 15 highest TN loading HUC8 watersheds to the Mississippi River contribute 74% of the TN load which ultimately reaches the river. The other 30 watersheds contribute the remaining 26% of the load to the Mississippi.

Total N yield estimated from SPARROW modeling showed that the urban dominated Mississippi River Twin Cities watershed delivered TN yields comparable to many other rural southern Minnesota watersheds (Figure 4).

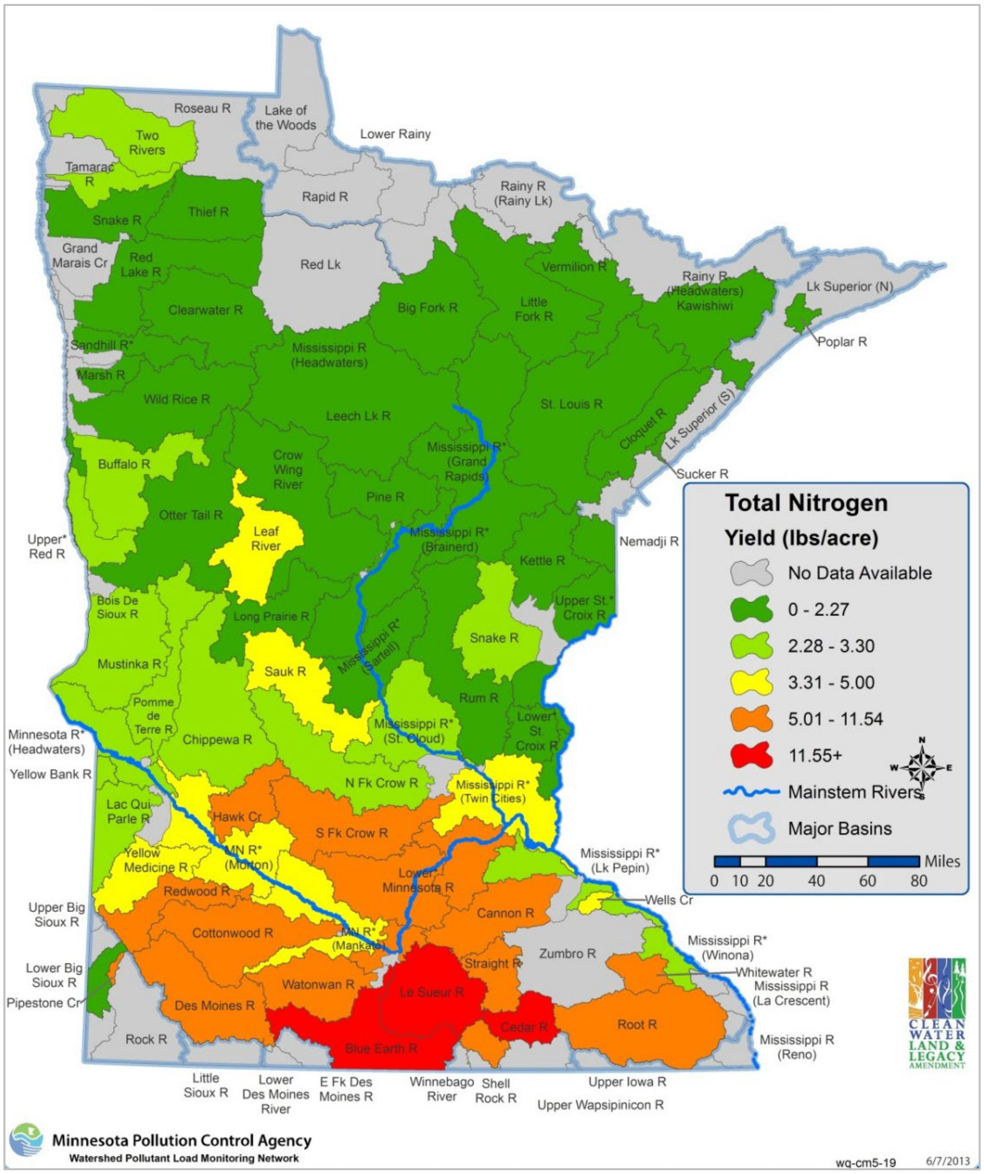


Figure 3. Monitoring-based annual TN yields near the outlet of each watershed. Average of available annual yield information between 2007 and 2009.

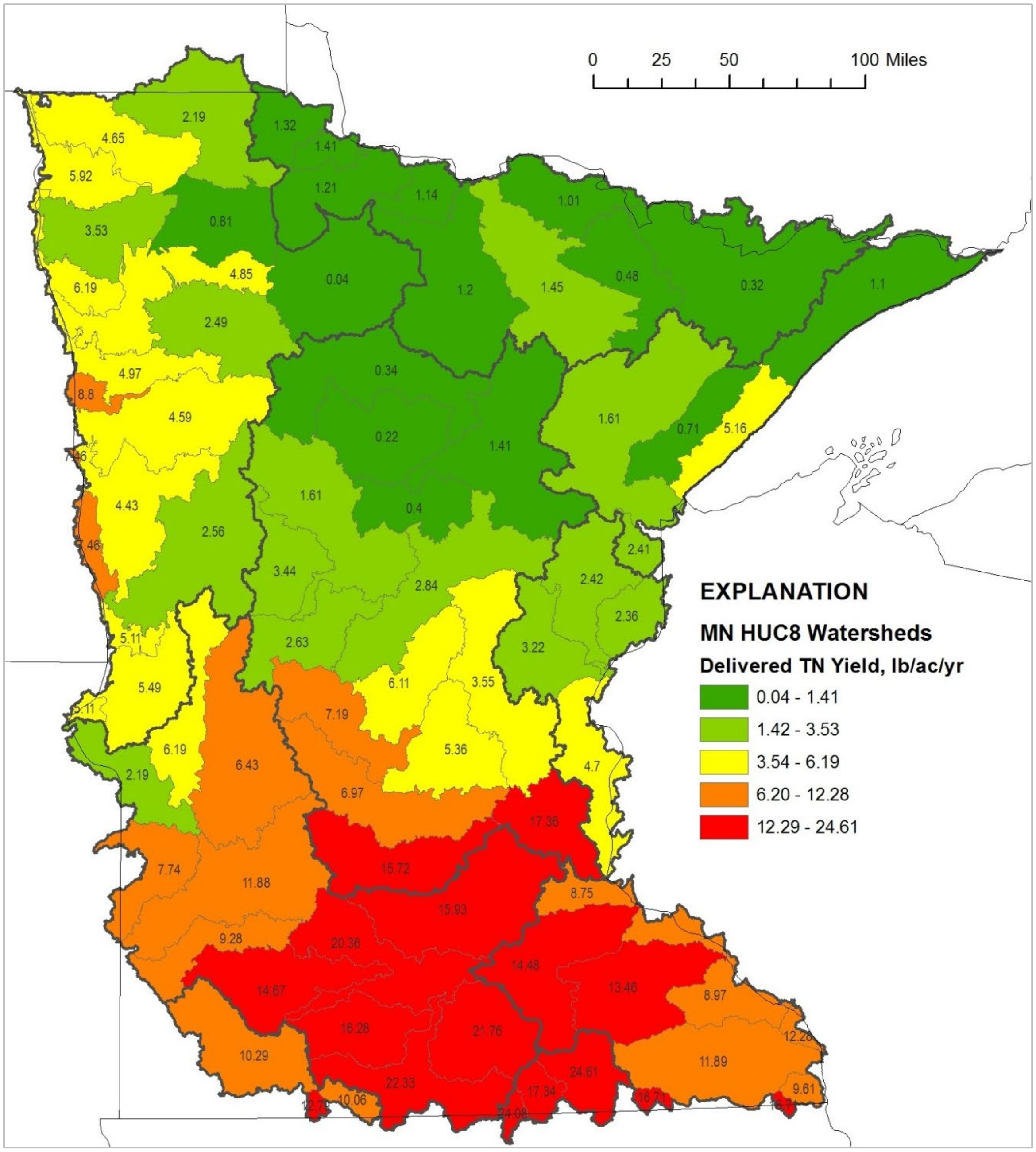


Figure 4. SPARROW model simulated incremental TN yields at the outlet of HUC8 watersheds (or state borders for watersheds cut-off by the state border).

Trends

Previous studies of N trends in Minnesota rivers and streams showed that *TN loads* increased since the 1970s and 1980s in the Red River of the North, Mississippi River, and Minnesota River. *Nitrate loads* had been found to have increased in the Mississippi and Minnesota Rivers between 1976 and 2005. Previous studies showed that *nitrate concentration*s were increasing in southeastern Minnesota streams and parts of central Minnesota, but that the downstream half of the Minnesota River generally showed no significant trend or a decrease. Previous studies also showed that river ammonium concentrations declined significantly over the 1980s and 1990s, likely in response to municipal wastewater upgrades and possibly also from feedlot and manure management improvements.

For this study, we evaluated flow-adjusted nitrite+nitrate-N (nitrate) concentration trends at 51 mainstem river and major tributary river monitoring sites throughout the state. The statistical trend analyses were performed with the QWTREND model, which was developed to evaluate periods of both increases and decreases which can occur at the same site over the period of record. River flow data was paired with nitrate monitoring results over a timeframe beginning during the mid-1970s and ending between 2008 and 2011.

Long-term (30-36 years) flow-adjusted nitrate concentration changes on the mainstem rivers are shown in Figure 5. The Mississippi River, which has very low nitrate concentrations in the north and less than 3 mg/l in the southern part of the state, showed increasing concentrations between 1976 and 2010 at most sites on the river, with overall increases ranging between 87% and 268% everywhere between Camp Ripley and LaCrosse. During recent years (i.e., 5-15 years prior to 2010), nitrate concentrations were increasing everywhere downstream of Clearwater on the Mississippi River at a rate of 1-4% per year, except that no significant trend was recently detected at Grey Cloud and Hastings in the Metro region.

Increasing nitrate concentration trends were also found in the Cedar River (113% increase over a 43-year period) and the St. Louis River in Duluth (47% increase from 1994 to 2010).

Not all locations in the state, however, are showing increasing trends. While nitrate concentrations remain very high in the downstream stretches of the Minnesota River (FWMC over 6 mg/l), two monitored sites (Jordan and Fort Snelling) showed a slight increase from 1979-2005, followed by a decreasing trend between 2005-06 and 2010-11. During recent years, all sites on the Minnesota River and most tributaries to the Minnesota River evaluated for trends have been either trending downward or have shown no trend (through 2009-11). Additionally, a few tributaries to the Mississippi River have also shown decreasing nitrate trends during the 6-8 year period prior to 2010, including the Rum, Straight, and Cannon Rivers.

Some other rivers have shown no significant trends since the mid-1970s, including the Rainy, West Fork Des Moines, and Crow Rivers. The Red River showed significant increases before 1995, but no significant trends between 1995 and 2010.

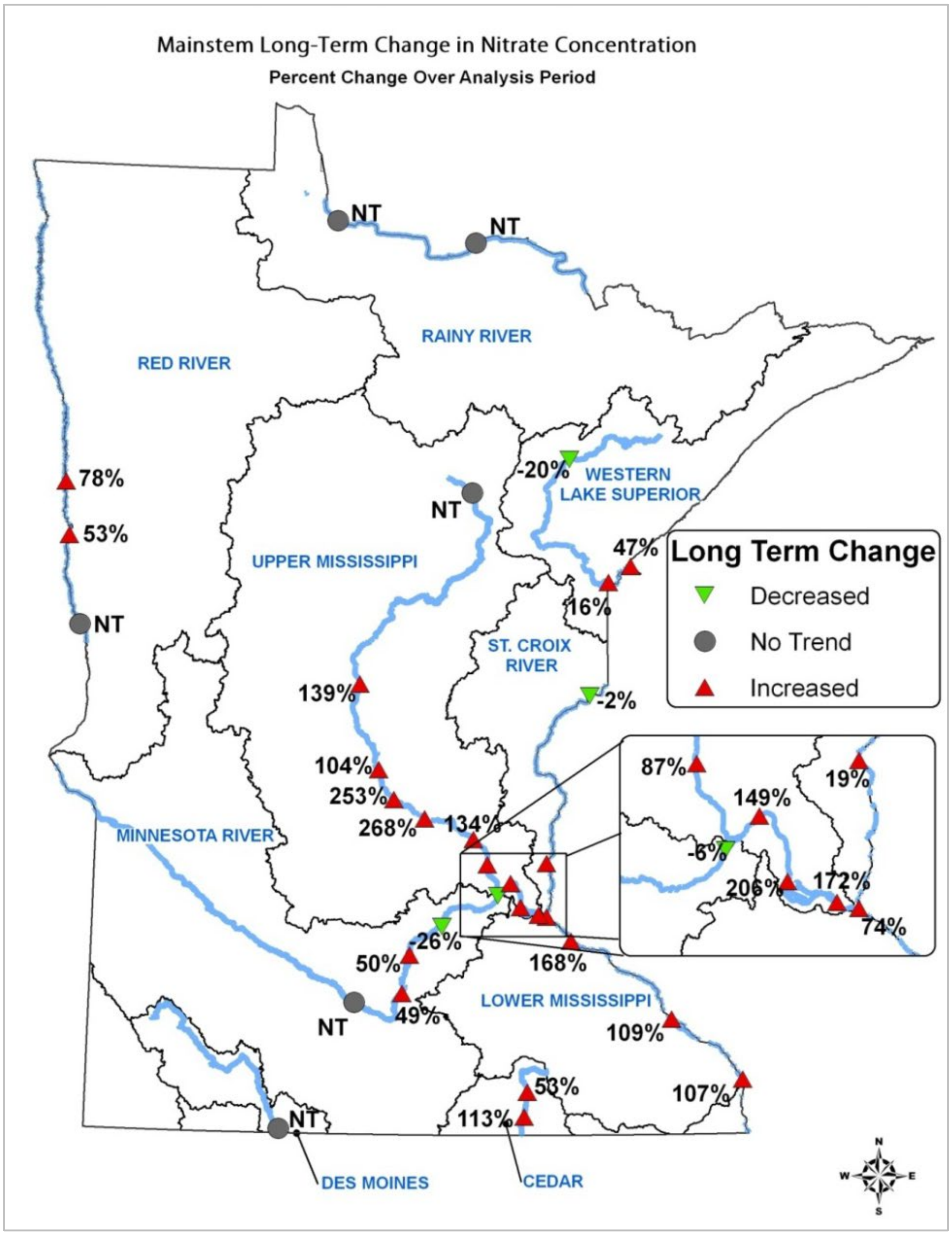


Figure 5. Long-term overall nitrate concentration trends (from mid to late 1970s until 2008-11) at mainstem river monitoring sites. Concentrations were adjusted for flow and changes are statistically significant at p<0.1.

Sources and pathways

Nitrogen source contributions to surface waters during average, wet and dry weather periods were estimated for each major basin and statewide. The estimated annual statewide TN (hereafter referred to as N) contributions reaching surface waters during an average precipitation year are shown in Figure 6. Results are intended for broader management planning decisions and should not be used in place of Total Maximum Daily Load (TMDL) studies or detailed local assessments based on site specific water quality monitoring and modeling data.

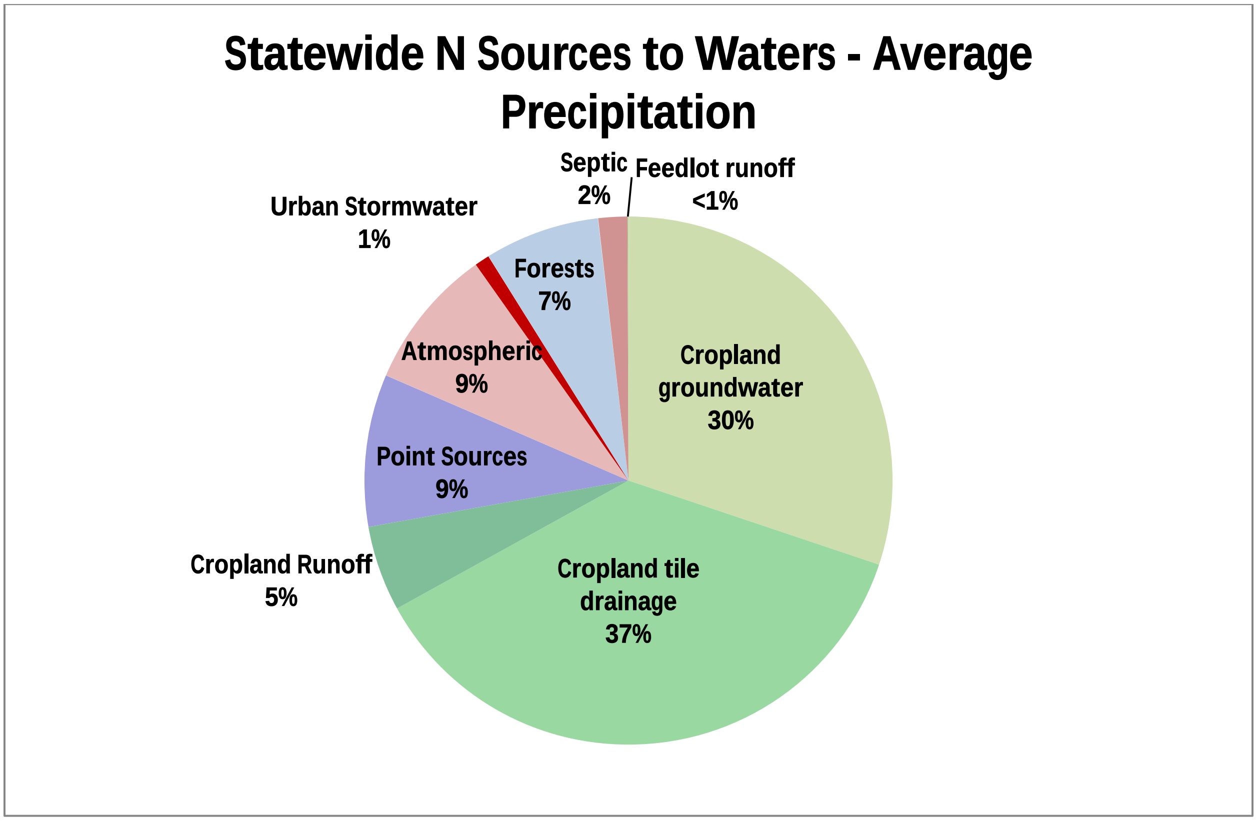


Figure 6. Estimated statewide N contributions to surface waters during an average precipitation year (rounded to whole numbers).

Cropland sources

Cropland N loads were estimated for three different pathways: surface runoff, tile-line transport, and leaching to groundwater and its subsequent underground movement to surface waters. Cropland sources were estimated by taking published field research results about N losses to water and then using GIS data-bases to extrapolate field-research results to larger scales. Cropland N source estimates were based on available site-specific data and watershed characteristics, adjusted for crops, geologic sensitivity, soils, climate, fertilizer rates, livestock manure availability, agricultural drainage, N losses within groundwater, and several other factors. The amount of N reaching surface waters from cropland varies tremendously, ranging from less than 10 pounds/acre on some cropland and more than 30 pounds/acre on other cropland.

According to the N source assessment conducted for this study, during an average precipitation year cropland sources contribute an estimated 73% of the statewide N load to surface waters. This statewide estimate is similar to SPARROW model simulations, which indicate that 70% of statewide N loading to surface waters is from agricultural sources. The cropland fraction of N load to surface waters varies by watershed, accounting for an estimated 89 to 95% of the N load in the Minnesota portions of the Minnesota River, Missouri River, Cedar River, and Lower Mississippi River Basins, and yet contributing less than 50% of the Upper Mississippi River Basin N (refer to Figure 8 for basin locations).

The emphasis of this study was estimating N loads from specific source categories to *surface waters*. Nitrogen sources to *land* were also estimated, since these sources can provide a general framework of understanding N potentially available for entering waters. Inorganic N becomes available to statewide cropland from several added sources to the soil, including commercial fertilizers (47%), legume fixation (21%), manure (16%), and wet plus dry atmospheric deposition (15%). Soil organic matter mineralization releases an estimated annual amount of inorganic N comparable to fertilizer and manure N additions combined. Septic systems, lawn fertilizer, and municipal sludge together account for about 1% of all N added to soils statewide.

Cropland surface runoff

Cropland N moves from soil sources to surface waters through two dominant pathways: 1) tile-line transport, and 2) leaching to groundwater and subsequent underground flow into surface waters. Compared to these two pathways, cropland surface runoff adds relatively little N to waters. Surface runoff contributes only 1-4% of N loads to waters in all major basins except the Lower Mississippi River Basin and Red River Basin, where runoff from cropland contributes 9-16% of the N load, respectively.

Cropland tile drainage

Nitrogen moving through tile-lines and subsequently into ditches and streams was found to be the pathway contributing the most cropland N to surface waters. During an average precipitation year, row crop tile drainage contributes an estimated 37% of the N load to Minnesota's waters overall, and contributes 67% of the N load in the heavily-tiled Minnesota River Basin. During a wet year, the fraction of N to waters from tile drainage increases to an estimated 43% of statewide N load and 72% of the Minnesota River N load. River monitoring results affirmed the importance of tile drainage contributions, showing that the highest N-yielding watersheds in the state are those which are intensively tiled.

Cropland nitrate leaching to groundwater

Nitrogen leaching into groundwater below cropped fields, and subsequently moving underground until it reaches streams, contributes an estimated 30% of N to surface waters statewide. Groundwater N can take hours to decades to reach surface waters, depending on the rate of groundwater flow and the distance between the cropland and stream. Nitrogen leaching into groundwater is the dominant pathway to surface waters in the karst dominated landscape of the Lower Mississippi River Basin, where groundwater contributes an estimated 58% of all N. Yet in the Minnesota River Basin, dominated by clayey and tile-drained soils, cropland groundwater only contributes 16% of the N to surface waters, on average.

Wastewater point sources

Wastewater point source loads, estimated largely from MPCA discharge permit records, release an annual average 29 million pounds of TN to statewide waters, accounting for 9% of the statewide N load according to the N source assessment. This is slightly more than the 7% point source contribution estimated from SPARROW modeling.

Wastewater point source loads are dominated by municipal wastewater sources, which contribute 87% of the wastewater point source N load discharges, with the remaining 13% from industrial facilities. The 10 largest wastewater point source N loading facilities collectively contribute 67% of the point source TN load. Nearly half (49%) of the wastewater point source N discharges occur within the Twin Cities Metropolitan Area. River monitoring shows that six million pounds of N (on average) is gained in major rivers as they pass through the Twin Cities area, which equates to a 3.5% increase.

Wastewater point source N additions from large urban areas can contribute similar loads as many croplands draining from a similarly sized area. However, the wastewater N delivery to rivers is different than from cropland, as it enters waters at a few specific points as opposed to being dispersed across the watershed.

Other sources

Two other source categories, atmospheric deposition and forestland runoff, each contribute cumulative total statewide N loads comparable to wastewater point source N loads. While the N concentrations from atmospheric deposition and forest sources are much lower than wastewater discharges, the aerial extent of these two sources is vast, thereby accounting for the similar overall loads.

Nitrogen falling onto land from wet and dry atmospheric deposition was highest in the south and southeast parts of the state and lowest in the north and northeast where fewer urban and agricultural sources exist. Atmospheric deposition falling into lakes and streams was considered in the source assessment as a direct source of N into waters, contributing 9% of the statewide annual N load to waters. Correspondingly, the areas of the state with the most lakes and streams had the most atmospheric deposition directly into waters. Yet, relatively few other N sources are found in the northern Minnesota lakes regions, and a large fraction of N entering most lakes from atmospheric deposition will not leave the lake in streams. Low river N concentrations and loads are found in the northern lakes regions of the state.

Some N, typically less than three pounds/acre/year, is exported from forested watersheds. Forest N contributions are nearly negligible in localized areas and N levels in heavily forested watersheds are quite low. Yet since such a large fraction of the state is forested, the total cumulative N to waters from forested lands is estimated to be about 7% of the statewide N load.

Other statewide N sources contribute relatively small N loadings, including septic systems (2%), urban/suburban runoff (1%), feedlot runoff (0.2%) and water-fowl (<0.2%).

Source load differences among major basins

The load estimates in this study only quantify N source contributions originating in Minnesota portions of basins. Nitrogen source and pathway contributions from Minnesota portions of river basins vary considerably from one major river basin to another, as shown in Figure 7 (see also basin location map in Figure 8). For example, during an average precipitation year, cropland source contributions range between 16% and 95% of the estimated N load to the waters in each basin. Wastewater point source contributions range from 1% to 30% across the different basins, and contribute a higher fraction of the load where cropland sources are relatively low.

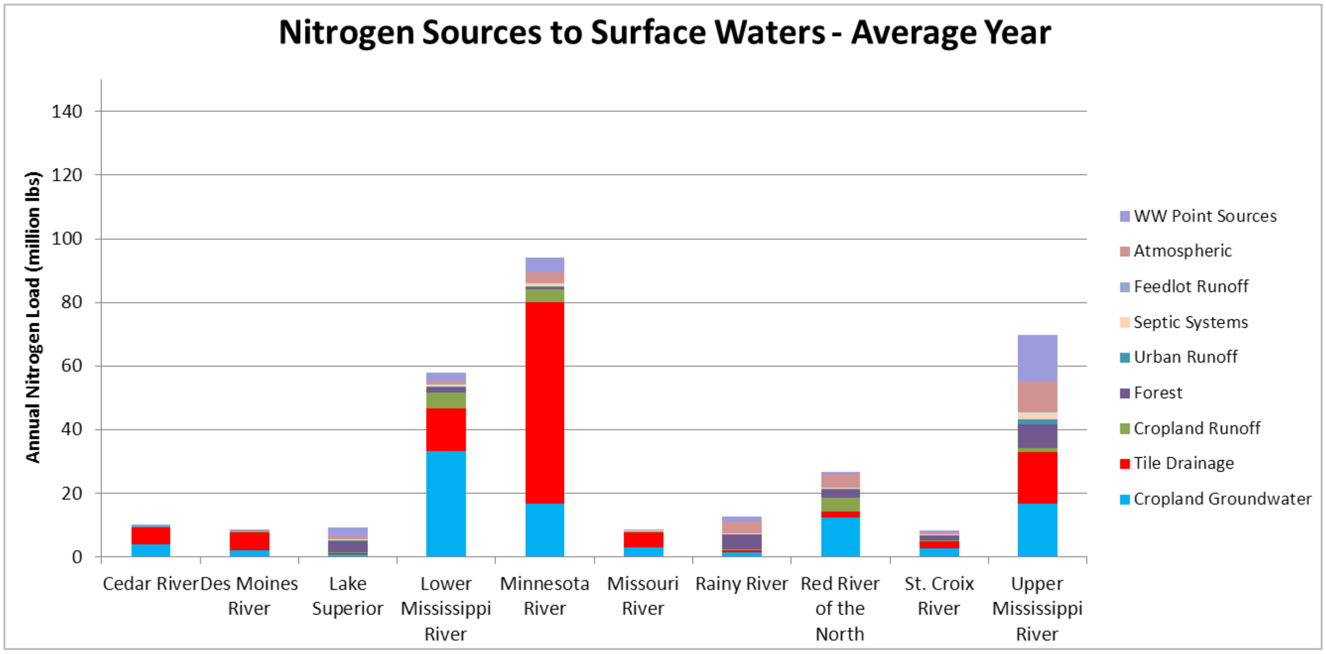


Figure 7. Estimated annual N loads to surface waters from different sources within the Minnesota portions of major basins during an average precipitation year.

Figure 8. Minnesota's major basins and watersheds.

Precipitation effects on source loads

Precipitation amounts have a pronounced effect on N loads. During a dry year, statewide N loads drop by 49% from average year loads (Figure 9). During a wet year, overall loads increase by 51%, as compared to an average year (Figure 10). The effects of precipitation are even greater in the Minnesota River Basin, where wet years have an estimated 70% greater N load, and dry years have 65% less N load.

Precipitation also affects the relative contributions from different N sources and pathways. During wet years, the cropland source contributions increase from 73% to 79% of the statewide N loads to waters. Agricultural drainage increases from 37% to 43% of the loads to surface waters during wet years, cropland runoff increases from 5% to 6%, and cropland groundwater remains at 30%. During dry years, the fraction of the load coming from wastewater point sources increases from 9% to 18%, whereas cropland sources are reduced to 54% of the estimated statewide N load.

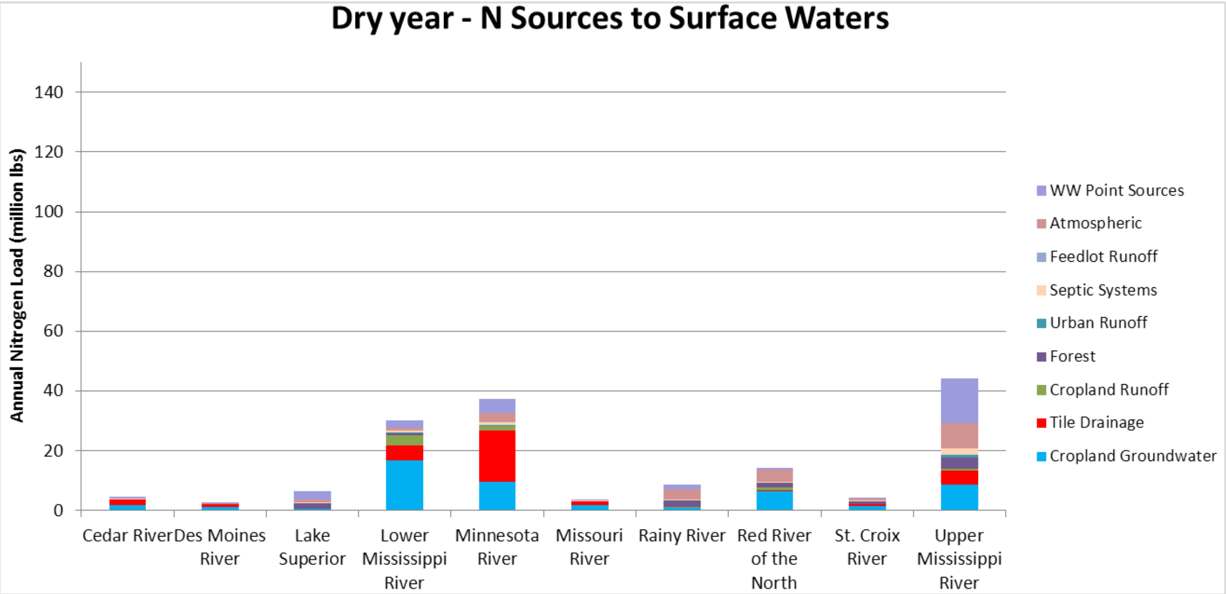


Figure 9. Estimated annual N loads to surface waters from different sources within the Minnesota portions of major basins during a dry year.

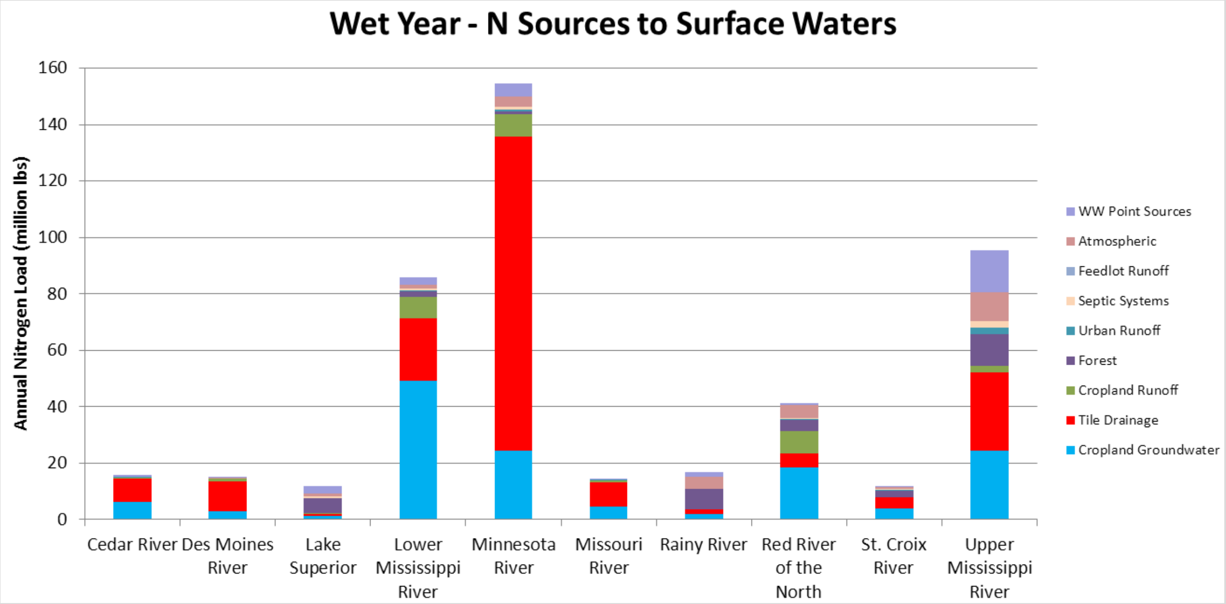
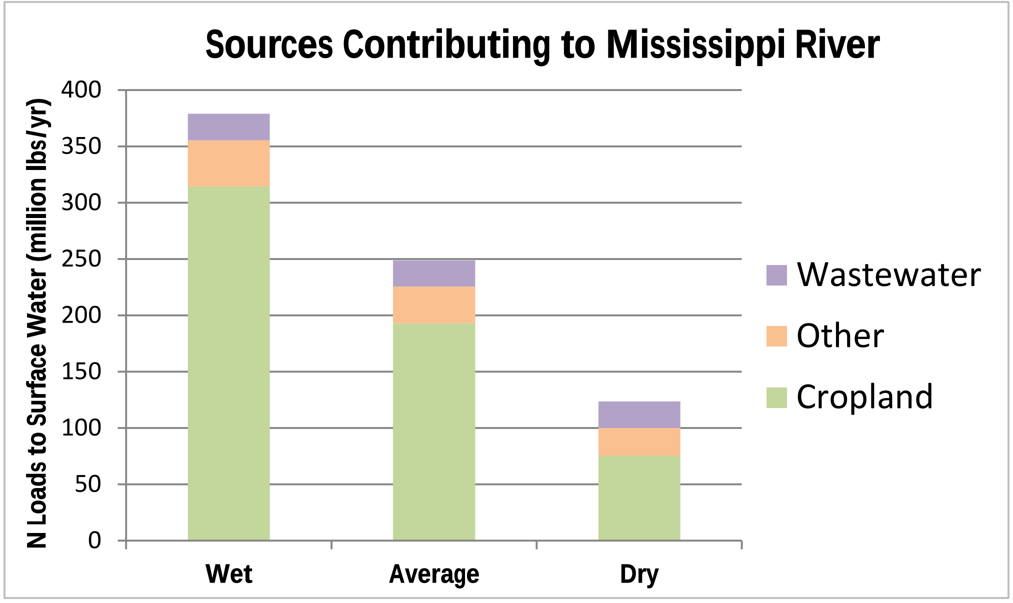


Figure 10. Estimated annual N loads to surface waters from different sources within the Minnesota portions of major basins during a wet year.

Sources to the Mississippi River

Just over 81% of the TN load to Minnesota waters is from watersheds which ultimately flow into the Mississippi River. If we look only at those Minnesota watersheds which contribute to the Mississippi River, source contributions during an average precipitation year are estimated as follows: cropland sources 78%, wastewater point sources 9%, and non-cropland nonpoint sources 13% (Figure 11).



Cropland source contributions increase to 83% for these watersheds during wet (high-flow) years, and point sources decrease to 6%. During a dry year, cropland sources represent an estimated 62% of N to waters and point sources contribute 19%.

Figure 11. Sum of N source contributions in watersheds which eventually reach the Mississippi River. The “other” category includes septic systems, atmospheric deposition directly into waters, feedlots, forested land and urban/suburban nonpoint source N. “Wastewater” includes municipal and industrial point sources.

Uncertainties and verification of sources

The source assessment conducted by the University of Minnesota and MPCA has some areas of uncertainty. All sources should be treated as large-scale approximations of actual loadings, and each source estimate could be refined with additional research. One particular area of uncertainty is the cropland groundwater component, due to: a) limited studies quantifying leaching losses under different soils, climate and management, and b) high variability in denitrification losses, which can occur as groundwater slowly flows toward rivers and streams.

Because of source assessment uncertainties, we compared the source assessment results with results from five separate approaches, as follows:

1) **Monitoring results** – HUC8 watershed and major basin scale monitoring results
2) **SPARROW modeling** – major N source categories (statewide)
3) **HSPF modeling** – Minnesota River Basin modeled estimates of sources, pathways and effects of precipitation
4) **Watershed characteristics analysis** – comparing watershed land and hydrologic characteristics with river N yields and concentrations
5) **Literature review** – existing studies in the upper-Midwest related to N sources and pathways

Mainstem river monitoring results compared reasonably well to the sum of the sources estimated by the source assessment during dry, average and wet conditions (Figures 12-14). The monitoring results were not expected to be the same as the sum of sources, since the sum of sources do not consider in-stream

N losses or lag times in groundwater N transport from sources to surface waters. Yet the fairly close agreement between the monitoring results and source load estimates provides one line of evidence that the source estimates may be reasonable.

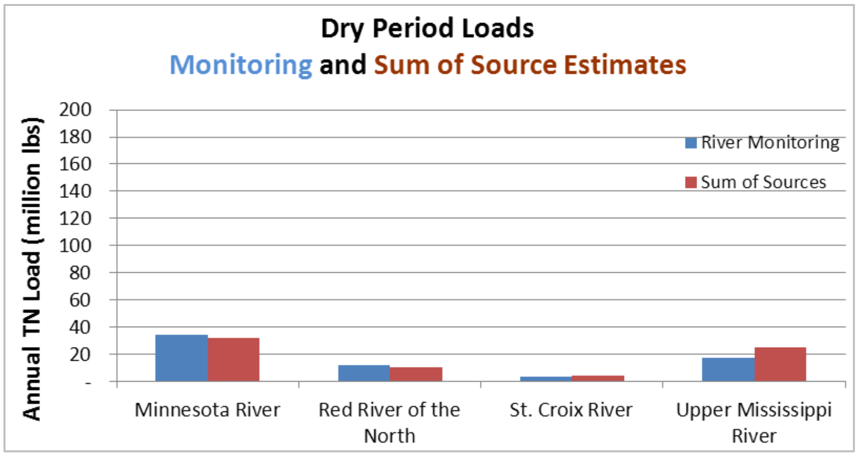


Figure 12. Dry period comparison of river monitoring average annual loads with the sum of estimated source loads.

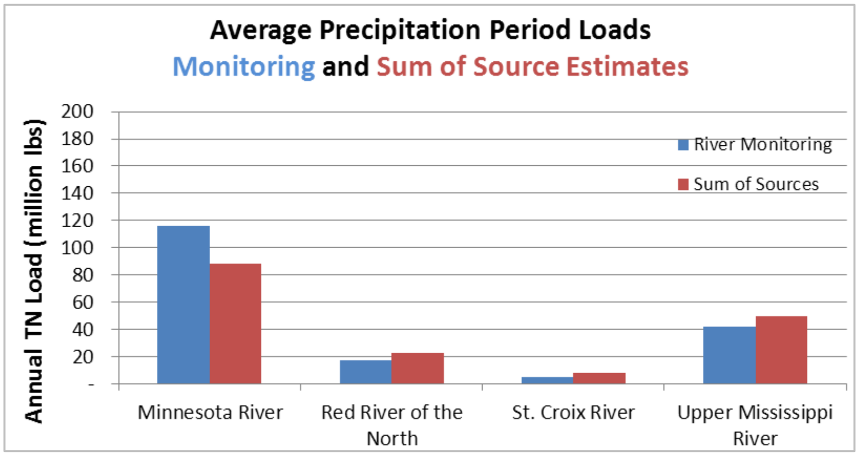


Figure 13. Average period comparison of river monitoring average annual loads with the sum of estimated

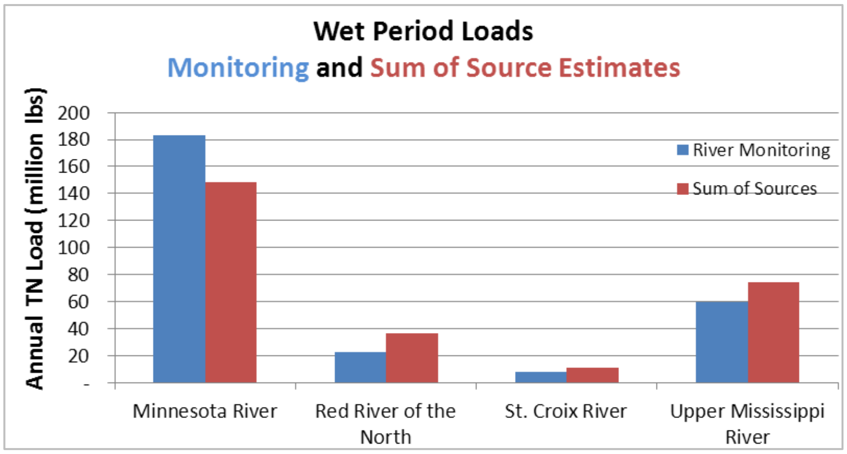


Figure 14. Wet period comparison of river monitoring average annual loads with sum of estimated source loads.

The SPARROW and HSPF model N source estimates were both consistent with the source assessment findings. SPARROW model results showed cropland sources as the dominant statewide N sources to Minnesota rivers, representing 70% of the source loads (Figure 15).

Using a markedly different modeling approach than SPARROW, the HSPF model results showed that the cropland sources represent 96.6% of the Minnesota River Basin nonpoint source inorganic N load to rivers, which was similar to a 97.6% estimate from the source assessment findings. The HSPF model results also showed similar flow pathways and wet weather effects on loads as compared to the source assessment findings.

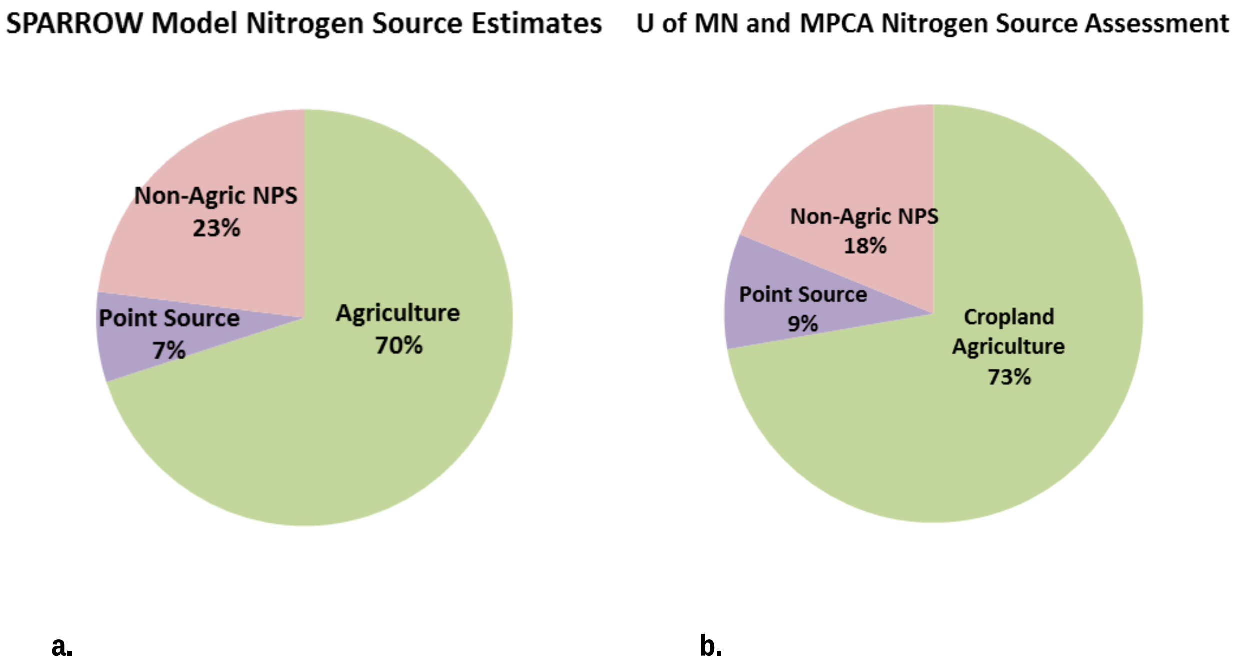


Figure 15. Comparing N source category contributions to Minnesota surface waters statewide during an average year using a) SPARROW model results, and b) N source assessment conducted for this study.

We also used statistical and non-statistical methods to compare watershed monitoring results with 18 watershed land use and hydrologic characteristics. These checks on the source assessment findings did not show inconsistencies with the source load findings, and they did show several relationships which support the source assessment findings. For example, a distinct pattern was observed between watershed nitrate levels and the percent of watershed with row crops over tile-drainage, sandy soils, and soils with a shallow depth to bedrock (Figure 16).

Statistical models of nitrate and TN concentration suggested that row crops over tile-drained soils and high groundwater recharge areas (sandy soils and/or shallow depth to bedrock) accounted for much of the nitrate concentration variability in the 28 HUC8 watersheds analyzed (r-squared exceeding 0.96). Statistical models also showed a similarly strong correlation between watershed N yields and two variables: 1) the amount of land with row crops over tile drainage, and 2) annual precipitation. For both the concentration and yield statistical models, the tile drainage variable exerted the strongest magnitude of influence, with two to five times the influence of the other explanatory variables.

All five ways of checking the findings corroborate the source assessment results and no major discrepancies were found. This increases our confidence that the source assessment is reasonably accurate and is useful for generally understanding large scale N load sources and pathways to Minnesota surface waters.

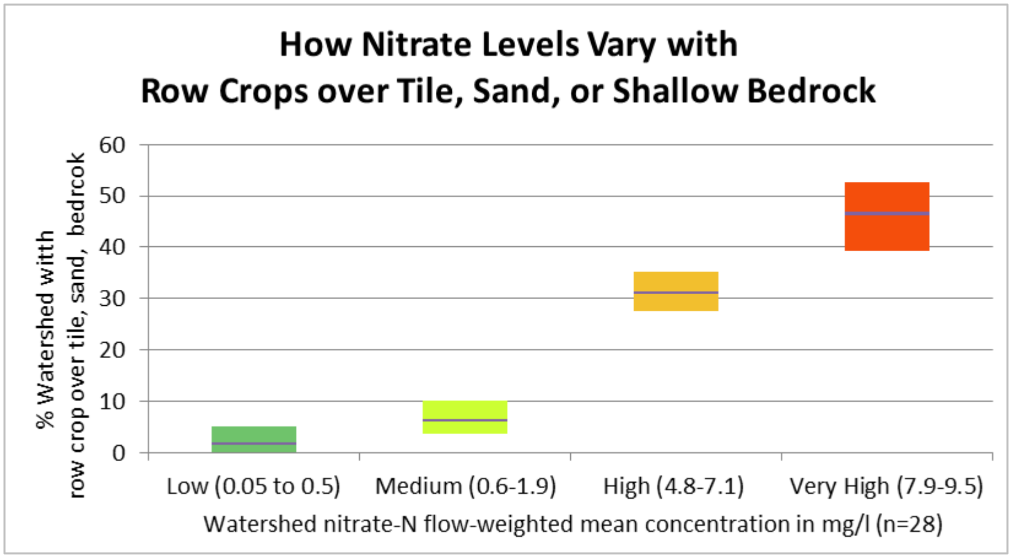


Figure 16. The range (colored bars) and average (dark line) percent of land in row crops underlain by tile-drainage (estimated), shallow bedrock or sandy subsoils. The four watershed nitrate classifications are based on river monitoring averages from two normal flow years within the period 2005-2009.

Potential ways to reduce nitrogen in surface waters

Because high N loading is pervasive over much of southern Minnesota, little cumulative large-scale progress to reduce N in surface waters will be made unless numerous large watersheds (i.e., the top 10 to 20 N loading watersheds) reduce N levels. Appreciable N reductions to major rivers and large downstream waters cannot be achieved by solely targeting individual small subwatersheds or mismanaged tracts of land. However, cumulative smaller scale changes repeated across much of the southern Minnesota landscape can make an appreciable difference in N loading.

Reducing nitrogen losses from cropland

Based on the N source assessment and the supporting literature/monitoring/modeling, meaningful regional N reductions to rivers can be achieved if Best Management Practices (BMPs) are adopted on acreages where there is a combination of: a) high N sources, b) seasonal lack of dense plant root systems, and c) rapid transport avenues to surface waters (which bypass denitrification N losses common in many groundwaters). These conditions mostly apply to row crops planted on tile-drained lands, but also include row crops in the karst region and over many sandy soils.

Further refinements in fertilizer rates and application timing can be expected to reduce river N loads and concentrations, yet more costly practices will also be needed to meet downstream N reduction goals.

BMPs for reducing N losses to waters can be grouped into three categories:

1) *In-field nutrient management* (i.e., optimal fertilizer rates; apply fertilizer closer to timing of crop use; nitrification inhibitors; variable fertilizer rates)
2) *Tile drainage water management and treatment* (i.e. shallower depth of tile drainage; control structures that let farmers adjust water levels; constructed and restored wetlands for treatment purposes; woodchip trench bioreactors; and saturated buffers)
3) *Vegetation/landscape diversification* (i.e. cover crops; perennials planted in riparian areas or marginal cropland; extended rotations with perennials; energy crops in addition to corn)

Through this study, a tool was developed by the University of Minnesota to evaluate the expected N reductions to Minnesota waters from individual or collective BMPs adopted on lands well-suited for the practices. The tool, called "Nitrogen Best Management Practice watershed planning tool" (NBMP), enables planners to gauge the potential for reducing N loads to surface waters from watershed croplands, and to assess the potential costs (and savings) of achieving various N reduction goals. The tool also enables the user to identify which combinations of BMPs will be most cost-effective for achieving N reductions at a HUC8 watershed or statewide scale.

We used the NBMP tool to assess N reduction scenarios in Minnesota (statewide and in specific HUC8 watersheds). Results from the NBMP tool were also compared to results from an Iowa study which used different methods to assess the potential for using agricultural BMPs to achieve N load reductions to Iowa waters. Both the Minnesota and Iowa evaluations concluded that no single type of BMP is expected to achieve large-scale reductions sufficient to protect the Gulf of Mexico. However, combinations of in-field nutrient management BMPs, tile drainage water management and treatment practices, and vegetation/landscape diversification practices, can together measurably reduce N loading to surface waters.

The N reduction potential varies by watershed (Figure 17). For example, if BMPs were implemented on all land suitable for the BMPs, the NBMP tool predicts a 22% river N reduction in the Root River Watershed and a 39% reduction in the LeSueur River Watershed. The North Fork Crow River Watershed could potentially achieve a 38% N reduction; however, it would need to rely more heavily on taking marginal cropland out of row crop production and replacing with perennials. The total net cost of achieving the reductions shown in Figure 19 is estimated to range from $22 to $47 million per watershed per year. The fertilizer BMPs were projected to save money and the majority of the estimated net costs were associated with the vegetation change BMPs.

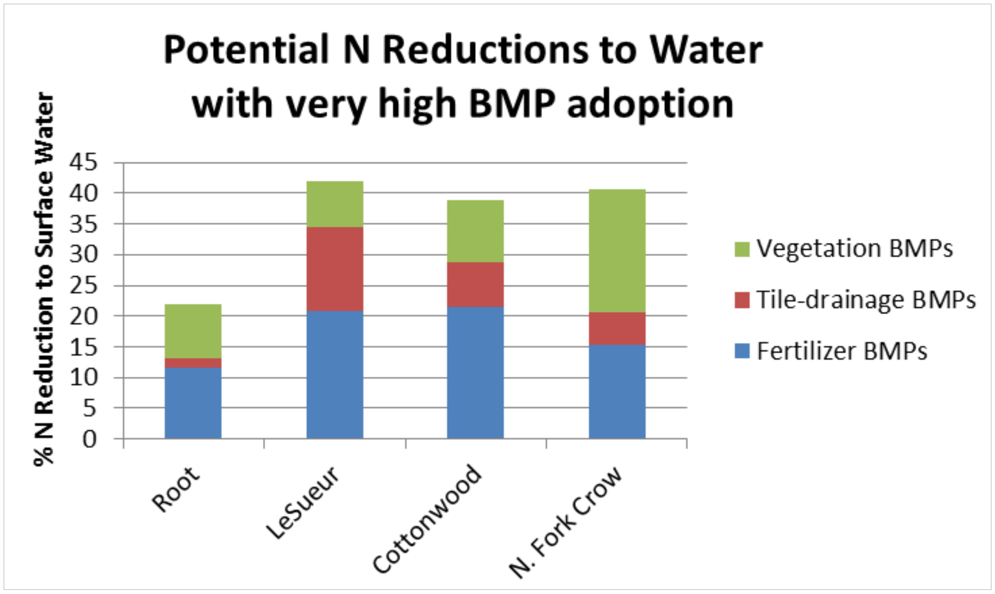


Figure 17 – Potential % N reductions to surface waters estimated with the NBMP tool when adopting BMPs on 100% of lands suitable for the following BMPs: optimal fertilizer rates and timing for corn (fertilizer BMPs), bioreactors and wetland construction/restoration and controlled drainage (tile-drainage BMPs), and plant cover crops and on marginally productive lands replace row crops with perennials (vegetation BMPs).

Statewide, river N loads can potentially be reduced by as much as 13% through widespread implementation of optimal in-field nutrient management BMPs, practices which can reduce fertilizer costs. To achieve 25% N load reductions, high adoption rates of a suite of other BMPs would need to be added to the in-field N management practices, and the net cost per pound of N reduced would increase.

The NBMP tool indicated that a 30-35% statewide reduction of cropland N losses to waters could be achieved if: over 90% of the corn land received optimal fertilizer rates applied in the spring; perennials were planted on 100 feet of either side of most streams; all tile drainage waters were treated in wetlands, bioreactors or otherwise were managed with controlled drainage structures; rye cover crops were planted each year on most row crops; and marginal cropland was retired to perennial vegetation. The projected net cost to install and manage these practices was over a billion dollars per year with recent crop prices and without further improvements in N reduction BMPs. Changes in crop economics and/or improvements to BMPs could reduce this net cost in the future.

Iowa predicted a 28% statewide nitrate reduction in water if cover crops were planted on row crops throughout the state. While Minnesota has a cooler climate, cover crops deserve further study in Minnesota due to a combination of desirable potential benefits to water quality and agriculture. If Minnesota can find ways to successfully establish and manage cover crops in row-cropped fields, and then achieve widespread use of cover crops, we could potentially reduce cropland N in Minnesota rivers by as much as 15 to 25% from this practice alone.

Tile-drainage water treatment BMPs are also part of a sequential combination of BMPs which could be employed in many areas to achieve additional N reductions to waters. Constructed wetlands and wetland restoration designed for nitrate treatment purposes remove considerable N loads from tile waters (averaging about 50%) and should be considered for certain riparian and marginal lands. Bioreactors may be an option for treating tile-line waters in upland areas where wetland treatment is less feasible, but they cost considerably more than wetlands for each pound of N reduced. If controlled drainage is used in combination with wetlands and bioreactors on lands well-suited for these BMPs, statewide N loads to streams can be reduced from these practices by an estimated 5-6%, and N loads in heavily-tiled watersheds can be reduced by an estimated 12-14%.

Perennial vegetation can greatly reduce N losses to underlying groundwater and tile drainage waters. When grasses, hay, and perennial energy crops replace row crops on marginally productive lands, N losses to surface waters are greatly reduced on the affected acreage. Under the current economic situation, the crop revenue losses when converting row crops to perennials, makes this practice less feasible on a widespread scale as compared to other practices, according to the results obtained with the NBMP tool. However, if changes occur and new markets develop for perennial crops, the economic picture could make this practice more feasible on larger acreages.

While this study largely focused on N removal BMPs, many BMPs provide additional benefits apart from reducing N. Any evaluation of recommended practices to reduce N should consider the additional costs and benefits of the BMPs. For example, BMPs such as constructed wetlands could potentially help reduce peak river flows through temporary storage of water, which could reduce flooding potential and improve water quality. Wetlands and riparian buffers also have a potential to increase wildlife habitat. Cover crops have added benefits of reducing wind and water erosion and potentially improving soil health and reducing pesticide use.

This study also focused on cost optimization of BMPs, rather than providing a full accounting of the net value of benefits from a reduced hypoxic zone in the Gulf of Mexico and other environmental benefits to Minnesota waters.

Wastewater nitrogen reduction

Wastewater point source N discharges can be reduced through two primary methods: 1) Biological Nutrient Removal (BNR), and 2) Enhanced Nutrient Removal (ENR) involving biological treatment with filtration and/or chemical additions.

BNR technologies, if adopted for all wastewater treatment facilities capable of adapting to this technology, would result in an estimated 43-44% N reduction in wastewater point source N discharges to rivers in the Upper Mississippi and Minnesota River Basins, and a 35% reduction in the Red River Basin. Because N loading from wastewater facilities is a relatively small statewide source compared to other sources, these reductions correspond with an estimated overall N reduction to waters of 9.3%, 2.2%, and 0.8% in the Upper Mississippi, Minnesota, and Red River Basins, respectively.

ENR technologies, if adopted for all wastewater treatment facilities capable of adapting to this technology, are estimated to result in a 64-65% N reduction in wastewater point source discharges to rivers in the Upper Mississippi and Minnesota River Basins, and a 51% reduction in the Red River Basin. These reductions correspond with an estimated overall N reduction to waters of 13.5%, 3.2%, and 1.2% in the Upper Mississippi, Minnesota, and Red River Basins, respectively.

In conclusion

Surface water N concentrations and loads are high throughout much of southern Minnesota, contributing to the N enriched hypoxic zone in the Gulf of Mexico, nitrate in excess of drinking water standards in certain cold water streams, and a potential to adversely affect aquatic life in a large number of Minnesota rivers and streams. Northern Minnesota has relatively low river N levels, and pollution prevention measures should be adopted in this area as landscapes and land management change.

Since the mid-1970s nitrate concentrations have continued to increase in the Mississippi River, yet they still average less than 3 mg/l (FWMC). The Minnesota River average nitrate concentrations remain high (above 6 mg/l FWMC), but were showing signs of stabilizing or decreasing in the 2005 to 2011 period. Trends are mixed in other rivers in the state, showing increases, decreases and several with no significant trend.

An estimated 73% of statewide N entering surface waters is from cropland sources and 9% is from wastewater point sources, with several other sources adding the other 18%. Most of the cropland N reaches waters through subsurface agricultural tile drainage and groundwater pathways, with a relatively small amount in overland runoff.

Reducing N levels in rivers and streams in southern Minnesota will require a concerted effort over much of the land in this region, particularly tile-drained cropland and row crops over permeable soils and shallow bedrock. Significant cumulative reductions are predicted when multiple practices are implemented over large acreages. Some progress toward reducing N losses to waters can be made by further optimizing in-field N management and temporarily retaining tile-line drainage waters in wetlands, bioreactors and behind controlled drainage structures. Cover crops and strategic establishment of perennial energy crops can greatly reduce N losses to waters, but need further development in Minnesota to make these practices more successful and adopted on more lands.