# G. Conclusions

## Concerns with nitrogen in waters

Nitrogen (N) affects in-state and downstream waters in three primary ways:

1. **Aquatic life toxicity** - Aquatic life have been found to be adversely affected by the toxic effects of elevated nitrate. The nitrate levels that harm aquatic life are currently being studied so that standards can be developed to protect Minnesota fish and other aquatic life.
2. **Gulf hypoxia** - The Gulf of Mexico receives about 6% of its N from Minnesota watersheds. The cumulative effects of multi-state N contributions are largely the cause of the hypoxic (low oxygen) zone in the Gulf of Mexico. While N can increase eutrophication in coastal waters, N has a less prominent role in affecting lake and stream eutrophication within Minnesota, which is mostly controlled by phosphorus.
3. **Nitrate in drinking water** - Fifteen streams, mostly in southeastern Minnesota, exceed a 10 mg/l standard established to protect potential drinking water supplies.

## River nitrogen conditions and loads

### Stream N 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 southern Minnesota, most river and stream sites exceed 5 mg/l at least occasionally. Most northeastern Minnesota streams have nitrate concentrations which remain less than 1 mg/l. Streams in northwestern Minnesota have nitrate that is typically less than 3 mg/l, even during peak times.

Total Nitrogen (TN) concentrations exhibit the same 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-N (ammonium). Ammonium concentrations are less than 1 mg/l even during peak times at 99% of rivers and streams in the state, and median concentrations are mostly less than 0.1 mg/l. River ammonium concentrations decreased substantially in the 1980's and 1990's, according to previous studies.

### Mainstem river loads

Monitoring-based annual TN loads show that most of the state's TN load leaves the state in the Mississippi River. Nearly 211 million pounds of TN leaves Minnesota per year in the Mississippi River at the Minnesota-Iowa border, on average, with just over three-fourths originating in Minnesota watersheds, and the rest coming from Wisconsin, Iowa and South Dakota. This compares to about 37 million pounds in the Red River at the Minnesota-Canadian border (17 million pounds from Minnesota and the rest mostly from North Dakota). The highest TN loading tributary to the Mississippi River is the Minnesota River. The Minnesota River adds about twice as much TN as the combined loads from the Upper Mississippi and St. Croix Rivers. This is not because the Minnesota River contributes more flow, but because its TN concentrations are so much higher than the other rivers, four to eight times higher than the Upper Mississippi and St. Croix Rivers, respectively.

South of the Twin Cities, tributaries from Wisconsin and Minnesota contribute additional TN to the Mississippi River. Only small amounts of N are lost in the mainstem rivers, unless the water is backed up in quiescent waters. In the river stretch between the Twin Cities and Iowa, some TN is lost when the river flow slows in Lake Pepin and in river pools behind lock and dams. Monitoring based loads show than an average 9% N loss occurs in Lake Pepin. An additional 3% to 13% of the River N is estimated to be lost in the collective pools along the 168 mile Mississippi River stretch between the Twin Cities and Iowa. The net effect of the TN additions and TN losses in the Lower Mississippi Basin is an average 37 million pound load increase between the Twin Cities and Iowa.

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. Total nitrogen loads in the Minnesota, Mississippi, and St. Croix Rivers 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 of March through July. This is due to both river flow and TN concentration increases during these months.

## Priority watersheds

Both monitoring and modeling show that the highest N yields occur in south central Minnesota, where TN flow-weighted mean concentrations (FWMCs) typically exceed 10 mg/l and yields range from about 15 to 25 pounds/acre/year. The second highest TN concentrations and yields are found in southeastern and southwestern Minnesota watersheds, which typically have TN FWMCs in the 5 to 9 mg/l range and yields between 8 and 15 pounds/acre/year.

Watersheds in the northern two-thirds of the state have much lower nitrate and TN concentrations, with TN FWMCs in northeastern Minnesota less than 1.5 mg/l and yields from 0.1 to 3 pounds/acre/year. Total N FWMC and yields are higher in the northwestern part of the state as compared to the northeast.

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

## River nitrate trends

Flow adjusted nitrate concentrations in the Mississippi River increased between about 1976 and 2010 at most regularly monitored sites on the river, with overall increases ranging between 87% and 268% everywhere between Camp Ripley and LaCrosse. During recent years, nitrate concentrations have been increasing everywhere downstream of Clearwater at a rate of 1% to 4% per year, except that no significant trend has been detected at Grey Cloud and Hastings in the Metro region. Another study by the National Parks Service and others showed that nitrate and TN loads also increased in the Mississippi River between 1976 and 2005 (see Chapter C2). Because over one-third of the Mississippi River N loads are influenced by groundwater baseflow, ongoing monitoring reflects a mix of waters having recently entered the soil and water, along with waters which entered the soil years to decades ago and are just now starting to reach surface waters.

Increasing nitrate concentration trends were also found in the Cedar River (113% over a 43-year period) and the St. Louis River in Duluth (47% increase from 1994 to 2010). The Red River showed significant increases before 1995, but no significant trends between 1996 and 2010.

Not all locations in the state, however, are showing increasing trends. The two monitored sites on the downstream portion of the Minnesota River (Jordan and Fort Snelling) showed a slight increase from 1979 to 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 have been either trending downward or have shown no trend. Additionally, some tributaries to the Mississippi Rivers have also shown decreasing nitrate trends in recent years, including the Rum, Straight, and Cannon Rivers.

Other rivers in the state have shown no significant trends since the mid-1970s, including the Rainy River, West Fork Des Moines, and Crow Rivers.

Trend studies published elsewhere showed many similarities to the findings in this study; yet the magnitude of percent change was often found to be higher in this study.

## Nitrogen sources

### Cropland

The amount of TN (hereinafter referred to as "N") reaching surface waters from cropland varies tremendously, depending on the crops, tile drainage practices, cropland management, soils, climate, geology and other factors. Annual N losses to surface waters are less than 10 pounds/acre/year on some cropland and over 30 pounds/acre/year on other cropland.

According to the N source assessment, during an average precipitation year, cropland sources contribute an estimated 73% of the statewide N load to surface waters and 78% of the N load to the Mississippi River. The statewide estimates are similar to the SPARROW model results, which indicate that 70% of N entering surface waters is from agricultural sources. The relative contribution of N loads to surface waters from cropland sources varies by watershed. Cropland sources account 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; whereas cropland N accounts for 49% of the Upper Mississippi River Basin N sources. The statewide fraction of N coming from cropland sources also varies with climate, increasing from 72% of statewide N load during an average precipitation year to 79% during a wet year. During a dry year, cropland sources are still the highest N loading sources, but are reduced to 54% of the estimated statewide source N load.

Inorganic N becomes available to crops from several added sources, including commercial fertilizers (47%), legume fixation (21%), manure (16%), and wet+dry atmospheric deposition (15%). The combination of septic systems, lawn fertilizer, and municipal sludge account for about 1% of all N added to soils statewide. Soil organic matter mineralization also contributes a substantial amount of annual inorganic N to soils, yet the precise amount is more difficult to measure or estimate than other sources. Estimates of net mineralization from this study suggest that statewide mineralization from cropland releases an annual amount of inorganic N that is comparable to N from fertilizer and manure additions combined.

Cropland N reaches surface waters through two dominant pathways: 1) tile-line transport, and 2) leaching to groundwater and subsequent flow to surface waters. Surface runoff from cropland adds relatively little N to waters, contributing 1% to 4% of major basin N loads, except that in the Lower Mississippi River and Red River Basin it cropland runoff contributes 9 and 16% of the N load, respectively.

#### Tile drainage

Tile drainage over row crops represents the highest cropland source pathway and highest overall source in the state. During an average precipitation year, row crop tile drainage contributes 37% of the N load to waters around the state, and contributes 67% of the N load in the heavily tiled Minnesota River Basin. During a wet year, tile drainage contributes an estimated 43% of statewide N loads to waters, and contributes 72% of the N load to the Minnesota River.

The highest N yielding watersheds in the state are those which are intensively tiled. Statistical analyses of Minnesota watershed characteristics indicated that the amount of tile drainage (estimated) explained nitrate and TN variability more than any of the 17 other factors examined. Other Midwest studies also showed a direct correlation between the amount of estimated tiled land and N levels entering waters.

#### Cropland groundwater

Nitrogen leaching down into groundwater below cropped fields, and subsequently moving underground until it reaches streams, contributes an estimated 30% of N to statewide surface waters. Groundwater N can take from hours to decades or longer to reach surface waters, depending on the rate of groundwater flow and the flow path distance. 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.

If we include both the cropland and non-cropland groundwater N sources, 36% of the statewide N load to surface waters is estimated to be from groundwater. The groundwater source estimates have more uncertainty than other source estimates, due to limited data and high variability in leaching and groundwater denitrification rates. Yet, the importance of the groundwater pathway to surface waters was also supported by results from other studies in the state, region and nation, as referenced in Chapter E3.

### Wastewater point sources

Wastewater point sources discharge an estimated average annual TN load of 28.7 million pounds statewide. The loads are dominated by municipal wastewater sources, which were found to contribute 87% of the wastewater point source N load discharges, with the remaining 13% from industrial facilities. Nearly half (49%) of the point source N discharges occur within the Twin Cities Metropolitan Area. The 10 largest point source N loading facilities collectively contribute 67% of the point source TN load.

Wastewater point sources contribute an estimated 9% of the statewide N load according to the source assessment. This is similar to, but slightly more than, the 7% point source contribution estimated from SPARROW model results. River monitoring shows that the sum of the long-term average river N coming into the Twin Cities is 6 million pounds less than the N leaving in the Twin Cities near Prescott/Hastings. The 6 million pound average difference is a statistically insignificant 3.5% of the Mississippi River Load at Prescott.

When we divide the wastewater point source N discharge by the size of contributing sewershed areas in the Twin Cities region, we obtain an average of 14 pounds/acre/year from wastewater point sources. In higher density population areas, the N yield increases to 20 pounds/acre/year. SPARROW simulated TN yield in the urban dominated Mississippi River Twin Cities Watershed was 17.4 pounds/acre/year, similar to the yield range identified through the source assessment study. These N yields are comparable to many cropland yields, but are generally lower than intensively tiled row-crop areas. 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 forest, each contribute cumulative total statewide N loads that are comparable to wastewater point source N loads. While the N concentrations from these two other sources are much lower than wastewater, the aerial extent of these two sources is vast, thereby accounting for the comparable loads.

Atmospheric deposition is highest in the south and southeast parts of the state and lowest in the north and northeast where fewer urban and cropland sources exist. Atmospheric deposition falling directly into lakes and streams was considered in the source assessment as a direct source of N into waters, contributing about 9% of the statewide annual 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 into most lakes will not leave the lake in streams. Some N, typically less than 3 pounds/acre/year, is exported out of 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 adds up to about 7% of the statewide N load.

Other sources were very small by comparison, including septic systems (2%), urban/suburban nonpoint source N (1%), feedlot runoff (0.2%) and water fowl (<0.2%).

### Sources to the Mississippi River

Just over 81% of the total N load to Minnesota waters is in watersheds which end up flowing into the Mississippi River. If we look only at those Minnesota watersheds which drain into the Mississippi River, N source contributions during an average precipitation year are estimated as follows: cropland sources 78%, wastewater point sources 9%, and non-cropland nonpoint sources 13%. Cropland source contributions increase to 83% for these watersheds during wet (high-flow) years, while wastewater point sources decrease to 6%. During a dry year, cropland sources represent an estimated 62% of N to waters in this region and wastewater point sources contribute 19%.

## Reducing nitrogen in surface waters

Because high N levels are pervasive over much of southern Minnesota, little cumulative large-scale progress in reducing N in surface waters will be made unless numerous watersheds (i.e. the top 10 to 20 N loading watersheds) reduce N levels. Appreciable N reductions to surface waters at regional and state-level scales cannot be achieved by solely targeting reductions on relatively small subwatersheds or mismanaged land tracts.

## Cropland source reduction

Based on the N source assessment and the supporting literature/monitoring/modeling, meaningful regional N reductions to rivers can only be achieved if Best Management Practices (BMPs) are adopted on acreages where there is a combination of a) high N sources to soils, b) seasonal lack of dense plant root systems, and c) rapid transport avenues to surface waters (bypassing denitrification N losses which are common in some ground waters). These conditions mostly apply to row crops planted on tile-drained lands, but also include 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. tile spacing and depth; controlled drainage; constructed and restored wetlands for treatment purposes; 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, Nitrogen Best Management Practice watershed planning tool (NBMP), enables planners to gauge the potential for reducing N loads to surface waters from cropland, and to assess the potential costs of achieving various N reduction goals. The tool also enables the user to identify which BMPs will be most cost-effective for achieving N reductions at a HUC8 watershed or statewide scale.

We used the NBMP tool to assess numerous 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 evaluation 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 measurably reduce N loading to surface waters.

River N loads can potentially be reduced by as much as 13% statewide through widespread implementation of optimal in-field nutrient management BMPs, practices which also have the potential to reduce fertilizer costs. To achieve a 25% N load reduction, high adoption rates of a suite of more costly BMPs will need to be added to the in-field N management BMPs. The achievability and costs of N load reductions vary considerably from one region to another.

A 30% to 35% statewide reduction of cropland N losses to waters was projected to cost between 1 and 2 billion dollars per year with current crop prices and without further improvements in N reduction BMPs. The results also showed that 15% to 25% N load reductions can be made at a substantially lower cost.

Iowa predicted a 28% statewide nitrate reduction if cover crops were planted on row crops throughout the state. Cover crops deserve further study in Minnesota due to a combination of desirable potential benefits to water quality and agriculture. If Minnesota can become more successful at establishing and managing cover crops, and then achieve widespread adoption of this practice, we could potentially reduce N in Minnesota rivers by as much as 17% to 27% from this practice alone.

Tile-drainage water treatment BMPs are also part of the sequential combination of BMPs which can 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 in riparian and marginal lands. Bioreactors cost more than wetlands to reduce a given amount of N, but show promise if further improvements can be made to treat waters during high-flow times of the year. Bioreactors may be an option in upland areas where wetland treatment is less feasible. 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 by 5% to 6%, and N loads in heavily-tiled watersheds can be reduced by an estimated 12% to 14%.

Perennial vegetation provides large N reductions to underlying groundwater and tile drainage waters. When grasses, hay, and perennial energy crops replace row crops on marginally productive lands and riparian areas, N losses to surface waters are greatly reduced. However, the crop revenue losses when converting row crops to perennials, especially during times of high grain prices, makes this practice less feasible on a widespread scale as compared to other practices.

### Wastewater N reduction

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

BNR technologies, if adopted for all wastewater treatment facilities, would result in an estimated 43% to 44% N reduction in wastewater point source discharges to rivers in the Upper Mississippi and Minnesota River Basins, and a 35% reduction in the Red River Basin. These reductions correspond with an estimated overall N reduction to waters from all N sources by 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, are estimated to result in a 64% to 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 from all N sources by 13.5%, 3.2% and 1.2% in the Upper Mississippi, Minnesota, and Red River Basins, respectively.

## Recommendations for future study

Future research can improve the estimates in this study.

Source estimates to surface waters could be improved by conducting the following studies:

- further quantification of N leaching to groundwater for different soils, crops, N management and regions of the state
- evaluate denitrification losses within groundwater under different hydrogeologic settings (as groundwater moves between source area and stream)
- verify amount of cropland tile drainage that exists and determine recent rates of installation
- conduct new and expanded fertilizer and manure use surveys and incorporate the new information
- supplement the Point Source N concentration information with additional effluent monitoring data

Strategies for reducing N losses to waters can be better evaluated with:

- a tool which integrates N, phosphorus, and sediment reduction BMPs and associated costs so that the total costs and benefits are considered when planning for multi-purpose BMP adoption strategies
- additional information about BMPs under development, such as saturated buffers, cover crop use in Minnesota, perennial energy crop economics, and water retention strategies
- improved and updated baseline information on current fertilizer rates and timing practices on both land with, and without, manure additions
- costs for reducing wastewater point sources of N
- see further recommendations for future study at the end of Chapter F1