B5. Nitrogen Transport, Losses, and Transformations within Minnesota Waters

Author: Dennis Wasley, MPCA

Introduction

Nitrogen (N) losses and transformations can occur at each point along the flow pathway between source and final destination, including within soil, groundwater and surface water.

Nitrogen losses and transformations within the soil system were studied for Minnesota (MN) conditions as part of the agricultural N budget developed by Mulla et al., and which is included in Chapter D4 of this report.

Nitrogen losses can also occur within the groundwater and in the transition zone where groundwater moves into riparian areas and surface waters. A literature review related to denitrification losses of nitrate within groundwater, focusing on upper Midwest studies, is included in Appendix B5-1.

Once in surface waters, N can also be lost through denitrification, converted from inorganic forms (i.e., nitrate) to organic forms (i.e., algae), or transform from organic forms back into inorganic N. Because these processes within surface waters can transform large quantities of N, it is important to understand how these processes can affect N conditions in rivers and streams. For this study, N transformations and losses within surface waters were investigated, through a review of published findings and an analysis of unpublished data. These findings are summarized below and are included in their entirety in Appendix B5-2.

Summary of nitrogen transformation within Minnesota surface waters

The literature of the past two decades has greatly increased our understanding of N transport in surface waters. Generalizing the movement and transformations of total nitrogen (TN) in surface waters of MN is complicated given the wide range of aquatic systems and N loads delivered to those systems throughout the state. Nitrogen transport in surface waters is spatially and temporally variable, which also makes generalizations difficult.

Nitrogen is present in detectable amounts in most MN surface waters. In surface waters with relatively low N inputs, N is typically present in low concentrations of inorganic forms (often near detection limits), with the majority of N present in organic forms bound in various components of living and dead organisms. As N loading increases to a given surface water beyond its ability to assimilate N inputs, detectable amounts of dissolved inorganic nitrogen (DIN) are measured. In well oxygenated waters, DIN is typically present as nitrate (NO_3-N) with lesser amounts of nitrite (NO_2-N) and ammonia/ammonium. Ammonia and ammonium can also make up a portion of DIN in MN waters. It is most common in waters with low dissolved oxygen such as wetlands, the hypolimnion of stratified lakes, and during winter immediately downstream of wastewater treatment plants. Nitrification or uptake of ammonia+ammonium by organisms converts this form of N to other forms in oxygenated surface waters during the other seasons.

Many factors influence the transport of N in surface waters of MN, including N loading, residence time, temperature, nitrate concentration, discharge, depth, velocity, and land use. Some of these factors are inherently different based on the type of surface water. Wetlands and lakes are common in northeast MN along with relatively low N inputs, which both contribute to low N yields. Nitrate concentrations in streams of northeast MN are very low, often near detection limits. Yields of N from watersheds in south-central MN are much higher due to low densities of lakes and wetlands and higher inputs of N, especially during seasonally higher stream discharge. The concentration of TN in streams can drop during low flow periods in mid-late summer due to a combination of lower input loads and in-stream processing where inputs are not excessive. The reduction in mid-late summer TN concentration does not result in substantially reduced annual loads since the majority of TN is transported from late-March to mid-July when stream discharge is typically highest in MN rivers. Watersheds in southeast MN are unique to the other watersheds in the state due to the large inputs of high nitrate groundwater, which maintain elevated TN levels during low flow and, therefore, have less seasonal concentration fluctuations of TN than south-central MN.

Residence time is a key factor for N removal across all aquatic ecosystems. Residence time is basically the time it takes to replace the volume of water for a given surface water. Longer residence time allows for more interaction with biota (including bacteria) within a given aquatic resource. Streams typically have much shorter residence times compared to wetlands and lakes. Consequently, streams generally transport more N downstream than lakes and wetlands. The amount of N removed within streams generally decreases with stream size and N loading.

Special consideration was given to the Mississippi River downstream of the Minnesota River due to the unique rapidly flushed impoundments (navigational pools in the lock and dam system on the mainstem Mississippi) on this river and availability of models and monitoring data. In this river system and other rivers throughout the state, N loading is typically at its annual peak during spring and early summer when streamflow is seasonally higher. Lake Pepin, a natural riverine lake on the Mississippi River, removed only 6% to 9% of the average annual input load of TN during the past two decades. Lake Pepin has the longest residence time of all the navigational pools on the MN portion of the Mississippi River by a factor of at least 5. Upstream removal and loading reductions of N throughout the tributary watersheds is needed to substantially reduce downstream transport of N by the Mississippi River from Navigational Pools 1 to 8 during spring and early summer. Estimates of the collective impact of all the 168 miles of Mississippi River with navigational pools in MN, including Lake Pepin, range from removal of 12% to 22% of average annual input loads. Impressive N cycling has been documented in this system, but the input load simply overwhelms the capacity of the river to remove the majority TN inputs during most years.

Outputs from the SPARROW model are useful to illustrate annual downstream delivery of TN loads in MN streams and rivers. The general findings of this review and the SPARROW modeling indicate that 80% to 100% of annual TN loads to rivers are delivered to state borders unless a large reservoir with a relatively long residence time is located in the stream/river network downstream of a given headwater stream. Large headwater reservoirs such as Lake Winnibigoshish remove a larger proportion of inputs than riverine lakes such as Lake Pepin which has a much larger contributing watershed. Other approaches described in Appendix B5-2 based on mass balances estimated from monitored rivers also showed that the majority of annual TN loads to a given river reach are delivered to downstream reaches.

What is relatively clear from this review and analysis is that larger rivers with high TN loads like the Minnesota River deliver downstream most of the annual N load that reaches the river mainstem. The collective removal rate of N loading in MN's lakes, wetlands, ephemeral streams, and headwaters/streams is less certain. National models such as SPARROW can estimate the collective losses of TN for modeled rivers and streams of a given watershed (see Chapter B4).

Many factors influence the losses in smaller lotic systems (Table 1). Watersheds with extensive lakes and wetlands and modest N loading certainly remove or transform inorganic nitrogen inputs. Watersheds with extensive tile drainage and limited lakes and wetlands often transport large loads of inorganic nitrogen to watershed outlets with some removal in headwaters. The percentage of delivered load typically increases with proximity to large rivers in all watersheds. Weather and precipitation during any given year certainly influence transport dynamics within the watershed. Higher precipitation translates into greater loading and increased stream velocity, which both contribute to increased downstream transport of DIN. Drought conditions lead to reduced loading and lower stream velocities, which contribute to increased losses and transformations of inorganic nitrogen.

Table 1. Positive and negative factors that influence downstream movement of NO_X-N in MN.

Factor	Conditions that enhance N removal	Example	Conditions that generally reduce N removal	
Streamflow	Low flow	Drought	High flow	Wet periods/spring
Annual Precipitation	Low	Western MN	Moderate	Eastern MN
Depth	Shallow (inches)	Headwater streams	Deep (9 ft)	Impounded portion of Mississippi River
Carbon content of sediment	High organic content	Backwaters, impoundments, wetlands	"Clean" sand with low organic content	Main channel of large rivers
Input loads/concentration	Low	Northern MN watersheds	High	Southern MN watersheds
Season	Late summer	Low flows and high temperature	Early Spring	High flow and cool temperatures
Riparian area	Natural	Forested stream	Rock or concrete	Urban areas
Riparian wetlands	Common	Northern MN	Few	Ditches in southern MN
Temperature	Warm	Summer	Cold/cool	Winter

Lakes, including backwaters of rivers and wetlands, can remove and/or assimilate DIN inputs as long as inputs are not excessive. Long hydraulic residence times in these surface waters along with carbon rich sediments are key to removing inorganic nitrogen inputs. The overall impact of these surface waters on downstream transport of TN from MN is difficult to quantify, but it is certain that existing surface waters of these types currently reduce TN loads to downstream waters.

The comprehensive review of N losses and transformations within surface waters is found in Appendix B5-2.